PB190243

AIR POLLUTION ENGINEERING MANUAL

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE
Public Health Service

Reproduced by the
CLEARINGHOUSE
for Federal Scientific & Technical
Information Springfield Va. 22151

919

AIR POLLUTION ENGINEERING MANUAL

AIR POLLUTION CONTROL DISTRICT
COUNTY OF LOS ANGELES

Compiled and Edited
by
John A. Danielson

U.S. DEPARTMENT OF HEALTH, EDUCATION, AND WELFARE

Public Health Service
Bureau of Disease Prevention Environmental Control
NATIONAL CENTER FOR AIR POLLUTION CONTROL

Cincinnati, Ohio
1967

For sale by the Superintendent of Documents, U.S. Government Printing Office
Washington, D.C. 20402 - Price $5.75 cents

The ENVIRONMENTAL HEALTH SERIES of reports was established to report the results of scientific and engineering studies of man's environment; the community, whether urban, suburban, or rural, where he lives, works, and relaxes; the air, water, and earth he uses and re-uses; and the wastes he produces and must dispose of in a way that preserves these natural resources. This SERIES of reports provides for professional users a central source of information on the intramural research activities of the Centers in the Bureau of Disease Prevention and Environmental Control, and on their cooperative activities with state and local agencies, research institutions, and industrial organizations. The general subject area of each report is indicated by the letters that appear in the publication number; the indicators are

AP -- Air Pollution

RH -- Radiological Health

UIH -- Urban and Industrial Health

Reports in the SERIES will be distributed to requesters, as supplies permit. Requests should be directed to the Center identified on the title page.

Public Health Service Publication No. 999-AP-40

CHANGES TO

PUBLIC HEALTH SERVICE PUBLICATION NO. 999-AP-40

AIR POLLUTION ENGINEERING MANUAL

Page	Column		
25	1	Line 4 from bottom	lb/ft^2 <u>should be</u> lb/ft^3
35		Fig 13	$z = (2D_s)^{1.38}$ <u>should be</u> $z = (2D_s)^{1.138}$
51	1	Line 2 from bottom	...column 6 ÷ column 7 <u>should be</u> column 6 + column 7 ...
56	2	Lines 17, 18, and 19	In all three equations, $\left[\frac{rpm_1}{rpm_2}\right]$ <u>should be</u> $\left[\frac{rpm_2}{rpm_1}\right]$
64	2	Bottom line	$P' = 13\left[\frac{0.075}{0.375}\right]$ <u>should be</u> $P' = 13\left[\frac{0.075}{0.0375}\right]$
82	2	Line 15	(h_c) <u>should be</u> (h_o)
83		Fig 41	Identify curves (from upper to lower) as AIR TEMPERATURE--0°F, 100°F and 200°F.
85	1	Line 2 from bottom	0.094 lb/hr <u>should be</u> 0.094 lb/hr-ft
136		Fig 80	Caption -- (left) <u>should be</u> (right) and (right) <u>should be</u> (left).
202		Fig 134	$\Delta P = 9.37D\left[\frac{V}{100}\right]^{1.56}$ <u>should be</u> $\Delta P = 0.37D\left[\frac{V}{100}\right]^{1.56}$
366	1	Line 4 from bottom	40-ft radius <u>should be</u> 4-ft radius
609	2	Bottom line	The diaphragm is flexible and rises and falls to balance....<u>add</u>...vapor volume changes. The roof and shell limit the capacity of such vessels. Normal operating...
630-459		Fig. 452-459	Abscissas -- CAPACITY, millions of barrels <u>should be</u> CAPACITY, thousands of barrels. Ordinates -- PRICE or COST, millions of dollars should be COST, thousands of dollars.
634		Fig 462	The photograph is upside down.
697		Fig 518	Caption -- "Flow diagram of a contact-type wet-gas sulfur plant" <u>should be</u> "Flow diagram of a contact-type wet-gas sulfuric acid plant."
748		Fig 545	CODLER SECTION <u>should be</u> COOLER SECTION.
771		Table 225	On second line in column entitled Blood, lb/head, the entry "--" <u>should be</u> 55.

FOREWORD

As concern for the quality of the atmosphere has grown, so also has the response to that concern. Federal, State and local programs are assuming increasingly greater responsibility in the development and practice of the many disciplines that contribute to understanding and resolution of the air pollution problem.

Rapid program expansion imposes even greater demands for the dissemination of knowledge in the field of air pollution control. Much work has been accomplished by competent scientists and engineers. However, in many instances, the experience gained has not been transcribed and organized into a form readily accessible to those most in need of information.

We are pleased, therefore, to have the opportunity to make available this new volume, the Air Pollution Engineering Manual. Distilling as it does the equivalent of hundreds of man-years of painstaking engineering innovation in the air pollution control field under one cover, it should become a valuable--if not indispensable--tool.

The manual is an outgrowth of the practical knowledge gained by the technical personnel of the Los Angeles County Air Pollution Control District, long recognized as outstanding in the field. District personnel have worked closely with industry to develop emission controls where none formerly existed.

It will be noted that there are categories of industrial emissions that are not discussed. The reason is that engineering control applications are described for only those industries located in Los Angeles County.

The manual was originated as a training aid for District and industry engineers under the administrations of Mr. S. Smith Griswold, the former, and Mr. Louis J. Fuller, the current, Air Pollution Control Officer for the Los Angeles County Air Pollution Control District. The editorial and technical content were developed exclusively by the staff of the District. The staff, in turn, was supervised during the development of the manual by Mr. Robert L. Chass, Chief Deputy Air Pollution Control Officer and Mr. Robert G. Lunche, Director of Engineering. Mr. John A. Danielson, Senior Air Pollution Engineer, served as editor.

The U. S. Public Health Service, recognizing the need for such a manual, is pleased to serve as publisher.

John T. Middleton
Director
National Center for Air Pollution Control

This manual was prepared for publication by Mrs. Pauline Elliott, who did the composition and makeup, and Mr. W. Robert Mobley, Consultant, under the direction of Mr. Kenneth Cassel, Jr., at facilities of the U.S. Public Health Service in Cincinnati, Ohio.

PREFACE

This Air Pollution Engineering Manual deals with the control of air pollution at individual sources. This approach is unique because it emphasizes the practical engineering problems of design and operation associated with the many sources of air pollution. These sources reside in metallurgical, mechanical, incineration, combustion, petroleum, and chemical processes. Although the literature contains excellent data on some of these processes, no handbook or manual has ever been compiled to organize the data in this specialized branch of engineering until now. This manual should, therefore, fill a need.

That the air pollution problems of one area are different from those of another is well known. The air pollution problems presented here originate in industrial and commercial sources peculiar to the Los Angeles area. Consequently, some processes, such as the burning of coal in combustion equipment, are not mentioned. Furthermore, the degree of air pollution control strived for in this manual corresponds to the degree of control demanded by air pollution statutes of the Los Angeles County Air Pollution Control District. Many other areas require less stringent control and permit less efficient control devices.

This manual consists of 11 chapters, each by different authors, and 4 appendixes. The first five chapters treat the history of air pollution in Los Angeles County, the types of air contaminants, and the design of air pollution control devices. The remaining chapters discuss the control of air pollution from specific sources. A reader interested in controlling air pollution from a specific source can gain the information needed by referring only to the chapter of the manual dealing with that source. If he then desires more general information about an air pollution control device, he can refer to the chapters on control devices. First, however, he should read Chapter 1 because it cites for Los Angeles County the prohibitory rules that regulate the degree of control efficiency attained by the described equipment.

Sole responsibility for the information is borne by the District, which presents the manual as a contribution toward the advancement of national understanding of the control of air pollution from stationary sources.

Louis J. Fuller
Air Pollution Control Officer
County of Los Angeles

ACKNOWLEDGMENT

Under the provisions of the California law creating the Los Angeles County Air Pollution Control District, the Board of Supervisors is empowered to act as the Air Pollution Control Board. Responsible for supervision and policy determination for the District, their firm support of needed air pollution control measures has advanced engineering capability in this field to a high degree. The information gained in Los Angeles County is applicable to the improvement of air quality wherever air pollution is experienced. Without the support of this Board, the information presented here would not have been possible.

THE BOARD OF SUPERVISORS
OF LOS ANGELES COUNTY

BURTON W. CHACE, Chairman
Fourth District

FRANK G. BONELLI
First District

ERNEST E. DEBS
Third District

KENNETH HAHN
Second District

WARREN M. DORN
Fifth District

EDITORIAL REVIEW COMMITTEE

Robert L. Chass
Robert G. Lunche
Eric E. Lemke
Robert J. Mac Knight
John L. Mills

TECHNICAL ASSISTANCE

Ivan S. Deckert
William F. Hammond
William B. Krenz
John L. Mc Ginnity
Robert C. Murray
Robert T. Walsh
John E. Williamson

EDITORIAL ASSISTANCE

Jerome D. Beale
George Thomas
Edwin J. Vincent
Wayne E. Zwischer

GRAPHIC ART

Lewis K. Smith

BLANK PAGE

CONTENTS

CHAPTER 1. INTRODUCTION

THE LOS ANGELES BASIN 3
RULES AND REGULATIONS IN LOS ANGELES COUNTY 3
Regulation II: Permits 4
Regulation IV: Prohibitions 4
Rule 50: The Ringelman Chart 4
Rule 51: Nuisance 4
Rule 52: Particulate Matter 5
Rule 53: Specific Contaminants 5
Rule 53.1: Scavenger Plants 5
Rule 54: Dust and Fumes 5
Rule 56: Storage of Petroleum Products 5
Rules 57 and 58: Open Fires and Incinerators 5
Rule 59: Oil-Effluent Water Separators 5
Rule 61: Gasoline Loading Into Tank Trucks and Trailers 5
Rules 62 and 62.1: Sulfur Content of Fuels 5
Rule 63: Gasoline Specifications 6
Rule 64: Reduction of Animal Matter 6
Rule 65: Gasoline Loading Into Tanks 6
Rule 66: Organic Solvents 6
Rule 66.1: Architectural Coatings 6
Rule 66.2: Disposal and Evaporation of Solvents 6
ROLE OF THE AIR POLLUTION ENGINEER 6
Accomplishments of the Permit System 6
USE OF THIS MANUAL 6
General Design Problems 7
Specific Air Pollution Sources 7

CHAPTER 2. AIR CONTAMINANTS

INTRODUCTION 11
FACTORS IN AIR POLLUTION PROBLEMS 11
TYPES OF AIR CONTAMINANTS 12
Organic Gases 12
Current Sources in Los Angeles County 12
Hydrocarbons - 12 . . . Hydrocarbon derivatives - 12
Significance in Air Pollution Problem 14
Inorganic Gases 14
Current Sources in Los Angeles County 14
Oxides of nitrogen - 14 . . . Oxides of sulfur - 14 . . . Carbon monoxide - 15
Significance in Air Pollution Problem 15
Oxides of nitrogen - 15 . . . Oxides of sulfur - 15 . . . Carbon monoxide - 16 . . .
Miscellaneous inorganic gases - 16
Aerosols 16
Current Sources in Los Angeles County 16
Carbon or soot particles - 16 . . . Metallic oxides and salts - 17 . . Oily or tarry droplets - 17
Acid droplets - 17 . . Silicates and other inorganic dusts - 18 . . . Metallic fumes - 18
Significance in Air Pollution Problem 18
AIR POLLUTION CONTROLS ALREADY IN EFFECT 18
CONTROL MEASURES STILL NEEDED 18
Motor Vehicle Emissions 20
Additional Controls Over Stationary Sources 20
Organic Gases 20

Oxides of Nitrogen 21
Oxides of Sulfur 21
Other Contaminants 21

CHAPTER 3. DESIGN OF LOCAL EXHAUST SYSTEMS

FLUID FLOW FUNDAMENTALS 25
Bernoulli's Equation 25
Pitot Tube for Flow Measurement 25
Correction Factors 27
HOOD DESIGN 27
Continuity Equation 27
Air Flow Into a Duct 28
Null Point 28
Design of Hoods for Cold Processes 30
Spray Booths 32
Abrasive Blasting 32
Open-Surface Tanks 32
Design of Hoods for Hot Processes 34
Canopy Hoods 34
Circular high-canopy hoods - 34. . Rectangular high-canopy hoods - 38. . .
Circular low-canopy hoods - 39 . . Rectangular low-canopy hoods - 40. . .
Enclosures - 41
Specific Problems 42
Steaming tanks - 42 . . Preventing leakage - 42
Hood Construction 43
High-Temperature Materials 43
Corrosion-Resistant Materials 43
Design Proportions 43
Transition to Exhaust Duct 43
DUCT DESIGN 44
General Layout Considerations 44
Types of Losses 44
Inertia Losses 44
Orifice Losses 44
Straight-Duct Friction Losses 45
Elbow and Branch Entry Losses 45
Exhaust system calculator - 45 45
Contraction and Expansion Losses 47
Collection Equipment 47
Design Procedures 47
Methods of Calculation 47
Methods of Design 48
Calculation Procedures 49
Fan Static Pressure 50
Balanced-Duct Calculations 51
Blast Gate Method 52
Checking an Exhaust System 52
Illustrative Problem 52
Fan Curve Calculator 57
Corrections for Temperature and Elevation 57
Duct Construction 59
FAN DESIGN 60
Centrifugal Fans 60
Axial-Flow Fans 60
Fan Characteristics 61
Influence of Blade Shape 61
Geometrically Similar Fans 62
Multirating Tables 63
Fan Laws 63
Selecting a Fan From Multirating Tables 65
Construction Properties 65

Heat Resistance 65
Explosive-Proof Fans and Motors 65
Fan Drives 65
VAPOR COMPRESSORS 67
Types of Compressors 67
Positive-Displacement Compressors 67
Dynamic Compressors 68
Reciprocating Compressors 69
Use in Air Pollution Control 69
CHECKING OF EXHAUST SYSTEM 72
Theory of Field Testing 72
Quantity Meters 72
Velocity Meters 72
Pitot Tubes 72
Pitot Tube Traversing Procedure 72
Altitude and Temperature Corrections for Pitot Tubes 73
Swinging-Vane Velocity Meter 73
Calibrating the Velocity Meter 73
Uses of the Velocity Meter 74
COOLING OF GASEOUS EFFLUENTS 75
Methods of Cooling Gases 76
Dilution With Ambient Air 76
Quenching With Water 76
Natural Convection and Radiation 79
Forced-Draft Cooling 81
Factors Determining Selection of Cooling Device 86

CHAPTER 4. AIR POLLUTION CONTROL EQUIPMENT FOR PARTICULATE MATTER

INERTIAL SEPARATORS 91
Single-Cyclone Separators 91
Theory of Operation 91
Separation Efficiency 92
Pressure Drop 93
Other Types of Cyclone Separators 93
High-Efficiency Cyclone Separators 94
Multiple-Cyclone Separators 94
Mechanical, Centrifugal Separators 94
Predicting Efficiency of Cyclones 94
Method of Solving a Problem 95
WET COLLECTION DEVICES 97
Theory of Collection 99
Mechanisms for Wetting the Particle 100
Types of Wet Collection Devices 100
Spray Chambers 101
Cyclone-Type Scrubbers 101
Orifice-Type Scrubbers 101
Mechanical Scrubbers 101
Mechanical, Centrifugal Collector With Water Sprays 102
High-Pressure Sprays 102
Venturi Scrubbers 103
Packed Towers 104
Wet Filters 104
The Role of Wet Collection Devices 105
BAGHOUSES 105
Filtration Process 106
Mechanisms 106
Direct interception - 108. . . Impingement - 109 . . .Diffusion - 110 . .Electrostatics - 110
Baghouse Resistance 110
Clean cloth resistance - 110 . . Resistance of dust mat - 111 . . .
Effect of resistance on design - 115
Filtering Velocity 116

Filtering Media 118
Fibers 118
Cotton - 118 . . . Wool - 118 . . . Nylon - 118 . . Dynel - 118. . . Orlon and Dacron - 118. . .
Teflon - 119 . . . Glass - 119
Yarn 119
Filament yarns - 119 . . Staple yarns - 119
Weave 120
Plain weave - 120. . . Twill weave - 120. . . Satin weave - 120
Finish 120
Size and Shape of Filters. 121
Diameters of tubular filtering elements - 121 . . . Length of tubular bags - 121 . . .
Length-to-diameter ratio - 121. . . Multiple-tube bags - 122 . . . Envelope type - 122
Installation of Filters. 122
Arrangement 122
Bag Spacing 123
Bag Attachment 123
Bottom attachments - 123 . . . Top support - 123
Cleaning of Filters 124
Methods 124
Manual cleaning - 124. . . Mechanical shakers - 125. . . Pneumatic shakers - 125. . .
Bag collapse - 127 . . . Sonic cleaning - 127. . . Reverse airflow - 128. . .
Reverse-air jets - 128
Cleaning Cycles 130
Manually initiated cycles - 130. . . Semiautomatic cycles - 131 . . .
Fully automatic cycles - 131 . . . Continuous cleaning - 131
Disposal of Collected Dust 131
Baghouse Construction 132
Pushthrough versus Pullthrough. 132
Structural Design 132
Hoppers 132
Size - 132. . . Slope of hopper sides - 133. . . Gage of metal - 133 . . .
Use of vibrators and rappers - 133 . . . Discharge - 134
Maintenance. 134
Service 134
Bag Replacement. 134
Precoating 135
SINGLE-STAGE ELECTRICAL PRECIPITATORS. 135
History of Electrostatic Precipitation. 135
Origins of Electrostatic Principles 135
Early Experiments With Electrostatics on Air Contaminants. 137
Development of the First Successful Precipitator 137
Improvements in Design, and Acceptance by Industry 138
Advantages and Disadvantages of Electrical Precipitation 138
Mechanisms Involved in Electrical Precipitation 139
Diverse Applications of Electrical Precipitation 141
Construction Details of Electrical Precipitators 141
Discharge electrodes - 141 . . . Collecting electrodes - 141 . . .
Tubular collecting electrodes - 141. . . Removal of dust from collecting electrodes - 143. . .
Precipitator shells and hoppers - 144
High Voltage for Successful Operation. 145
Tube-type rectifiers - 145. . . Solid-state rectifiers - 145
Effects of Wave Form 145
Controlled Sparking Rate 146
Operating Voltage 146
Uniform Gas Distribution 146
Cost of Electrical Precipitator Installations 146
Theoretical Analysis of Precipitator Performance 147
Particle charging - 147. . . Particle migration - 148
Theoretical Efficiency 149
Deficiencies in Theoretical Approach to Precipitator Efficiency. 150
Effects of Resistivity 150

Methods of Reducing Reentrainment 152
Practical Equations for Precipitator Design and Efficiency 153
Effects of Nonuniform Gas Velocity 154
Important Factors in the Design of a Precipitator 156
Summary and Conclusions 156
TWO-STAGE ELECTRICAL PRECIPITATORS 156
Theoretical Aspects 158
Theory of Dust Separation 158
Particle charging - 159
Drift Velocity 159
Efficiency 160
Design Factors 160
Electrical Requirements 160
Air Capacity 161
Air Distribution 161
Auxiliary Controls 162
Construction and Operation 163
Assembly 163
Maintenance 163
Safety 163
Application 163
Two-Stage Precipitators of Special Design 165
Equipment Selection 165
OTHER PARTICULATE-COLLECTING DEVICES 166
Settling Chambers 166
Impingement Separators 166
Panel Filters 167
Precleaners 168

CHAPTER 5. CONTROL EQUIPMENT FOR GASES AND VAPORS

AFTERBURNERS 171
Direct-Fired Afterburners 171
Specifications and Design Parameters 171
Operation 173
Efficiency 174
Design calculations - 174
Installation costs 178
Catalytic Afterburners 178
Specifications and Design Parameters 178
Operation 180
Efficiency 184
Design calculations - 185
Installation Costs 187
BOILERS USED AS AFTERBURNERS 187
Conditions for Use 187
Manner of Venting Contaminated Gases 188
Adaptable Types of Equipment 189
Boilers and Fired Heaters 189
Burners 190
Safety 190
Design Procedure 190
Test Data 192
ADSORPTION EQUIPMENT 192
Types of Adsorbents 194
Use of Activated Carbon in Air Pollution Control 194
Saturation 194
Retentivity 195
Breakpoint 195
Heat of Adsorption 195
Carbon Regeneration 196
Equipment Design 196

Fixed-Bed Adsorber 197
Conical fixed-bed adsorber - 199
Continuous Adsorber 200
Pressure Drop 200
Operational Problems 201
Particulate Matter. 201
Corrosion 201
Polar and Nonpolar Compounds 201
VAPOR CONDENSERS 201
Types of Condensers 202
Surface and Contact Condensers. 202
Typical Installations 204
Condensers in Control Systems 204
Subcooling Condensate 205
Contact Condensers. 206
Sizing Contact Condensers 206
Surface Condensers. 206
Characteristics of Condensation. 206
Design of Surface Condensers 206
Applications. 210
GAS ABSORPTION EQUIPMENT 210
General Types of Absorbers 211
Packed Tower Design 211
Packing Materials 212
Liquid Distribution 212
Tower Capacity. 213
Tower Diameter 214
Number of Transfer Units (NTU) 216
Height of a Transfer Unit 217
Pressure Drop Through Packing 219
Illustrative Problem 219
Plate or Tray Towers 223
Types of Plates. 223
Bubble Cap Plate Tower Design 224
Liquid Flow 224
Plate Design and Efficiency. 224
Flooding 225
Liquid Gradient on Plate. 226
Plate Spacing 227
Tower Diameter 227
Number of Theoretical Plates 228
Illustrative Problem 228
Comparison of Packed and Plate Towers. 230
Vessels for Dispersion of Gas in Liquid 231
Spray Towers and Spray Chambers 231
Venturi Absorbers 231

CHAPTER 6. METALLURGICAL EQUIPMENT

FURNACE TYPES 235
Reverberatory Furnace 235
Cupola Furnace 236
Combustion Air 236
Methods of Charging 237
Preheating Combustion Air 237
Electric Furnace 238
Direct-Arc Furnace 238
Indirect-Arc Furnace 238
Induction Furnace 239
Resistance Furnace 239
Crucible Furnace 239

Tilting Furnace
Pit Crucible . . . 240
Stationary Crucible . . . 240
Pot Furnace . . . 240
STEEL-MANUFACTURING PROCESSES . . . 240
Open-Hearth Furnaces . . . 241
The Air Pollution Problem . . . 242
Hooding and Ventilation Requirements . . . 243
Air Pollution Control Equipment . . . 244
Electric-Arc Furnaces . . . 246
The Air Pollution Problem . . . 247
Hooding and Ventilation Requirements . . . 248
Air Pollution Control Equipment . . . 248
Baghouse dust collectors - 250. . Electrical precipitators - 252. . .Water scrubbers - 255
Electric-Induction Furnace . . . 250
The Air Pollution Problem . . . 256
Hooding and Ventilation Requirements . . . 256
Air Pollution Control Equipment . . . 256
IRON CASTING . . . 257
Cupola Furnaces . . . 258
The Air Pollution Problem . . . 258
Hooding and Ventilation Requirements . . . 258
Air Pollution Control Equipment . . . 258
Afterburners - 258. . Baghouse dust collectors - 260. . Electrical precipitators - 262
Illustrative Problem . . . 258
Electric-Arc Furnaces . . . 265
The Air Pollution Problem . . . 267
Hooding and Ventilation Requirements . . . 268
Air Pollution Control Equipment . . . 268
Baghouse dust collectors - 268. . Electrical precipitators - 268
Induction Furnaces . . . 268
Reverberatory Furnaces . . . 268
SECONDARY BRASS- AND BRONZE-MELTING PROCESSES . . . 270
Furnace Types . . . 270
The Air Pollution Problem . . . 270
Characteristics of emissions - 270. . Factors causing large concentrations of zinc fumes - 271
Crucible furnace--pit and tilt type - 273 . .Electric furnace--low-frequency induction type - 273
Cupola furnace - 274
Hooding and Ventilation Requirements . . . 274
Reverberatory furnace--open-hearth type - 274. . Reverberatory furnace--cylindrical type - 276
Reverberatory furnace--tilting type - 276. . Reverberatory furnace--rotary tilting type - 276. .
Crucible-type furnaces - 279. . Low-frequency induction furnace - 279. . Cupola furnace - 280
Air Pollution Control Equipment . . . 280
Baghouses - 280 . .Electrical precipitators - 281 . . Scrubbers - 281
SECONDARY ALUMINUM-MELTING PROCESSES . . . 284
Types of Process . . . 284
Crucible Furnaces . . . 284
Reverberatory Furnaces . . . 284
Fuel-Fired Furnaces . . . 284
Electrically Heated Furnaces . . . 285
Charging Practices . . . 285
Pouring Practices . . . 285
Fluxing . . . 286
Cover fluxes - 287. . Solvent fluxes - 287 . .Degassing fluxes - 287. . .
Magnesium-reducing fluxes - 287
The Air Pollution Problem . . . 288
Particle Size of Fumes From Fluxing . . . 289
Hooding and Ventilation Requirements . . . 289
Air Pollution Control Equipment . . . 290
SECONDARY ZINC-MELTING PROCESSES . . . 293
Zinc Melting . . . 293

The Air Pollution Problem 294
Zinc Vaporization 294
Reduction Retort Furnaces 294
Reduction in Belgian Retorts 294
The Air Pollution Problem 296
Hooding and Ventilation Requirements 296
Distillation Retort Furnaces 296
The Air Pollution Problem 297
Hooding and Ventilation Requirements 297
Muffle Furnaces 297
The Air Pollution Problem 298
Hooding and Ventilation Requirements 299
Air Pollution Control Equipment 299
LEAD REFINING 300
Reverberatory Furnaces 300
The Air Pollution Problem 300
Hooding and Ventilation Requirements 301
Air Pollution Control Equipment 301
Lead Blast Furnaces 302
The Air Pollution Problem 303
Hooding and Ventilation Requirements 304
Air Pollution Control Equipment 304
Pot-Type Furnaces 304
The Air Pollution Problem 304
Hooding and Ventilation Requirements 305
Air Pollution Control Equipment 305
Barton Process 305
METAL SEPARATION PROCESSES 305
Aluminum Sweating 305
Zinc, Lead, Tin, Solder, and Low-Melting Alloy Sweating 306
The Air Pollution Problem 306
Contaminants from aluminum-separating processes - 306. . .
Contaminants from low-temperature sweating - 306
Hooding and Ventilation Requirements 307
Air Pollution Control Equipment 308
Aluminum-separating processes - 308. . . Low-temperature sweating - 308
CORE OVENS 309
Types of Ovens 309
Heating Core Ovens 312
Core Binders 312
The Air Pollution Problem 314
Hooding and Ventilation Requirements 315
Air Pollution Control Equipment 315
FOUNDRY SAND-HANDLING EQUIPMENT 315
Types of Equipment 315
The Air Pollution Problem 316
Hooding and Ventilation Requirements 317
Shakeout grates - 317. . . Other sand-handling equipment - 318
Air Pollution Control Equipment 318
HEAT TREATING SYSTEMS 320
Heat Treating Equipment 320
The Air Pollution Problem 320
Hooding and Ventilation Requirements 321
Air Pollution Control Equipment 321

CHAPTER 7. MECHANICAL EQUIPMENT

HOT-MIX ASPHALT PAVING BATCH PLANTS 325
Introduction 325
Raw Materials Used 325
Basic Equipment 325
Plant Operation 325

The Air Pollution Problem 326
Hooding and Ventilation Requirements. 328
Air Pollution Control Equipment 328
Variables Affecting Scrubber Emissions 330
Collection Efficiencies Attained 332
Cost of Air Pollution Control Equipment 333
CONCRETE-BATCHING PLANTS 334
Wet-Concrete-Batching Plants 334
The Air Pollution Problem 334
Air Pollution Control Equipment 334
Cement-receiving and storage system - 335 . . . Cement weigh hopper - 336 . . . Gathering hoppers - 336
Dry-Concrete-Batching Plants 335
The Air Pollution Problem 336
Hooding and Ventilation Requirements. 337
Air Pollution Control Equipment 337
Dust created by truck movement - 337
Central Mix Plants 337
The Air Pollution Problem 337
Hooding and Ventilation Requirements. 338
Air Pollution Control Equipment 339
CEMENT-HANDLING EQUIPMENT 339
The Air Pollution Problem 339
Hooding and Ventilation Requirements 339
Receiving Hoppers. 339
Storage and Receiving Bins 339
Elevators and Screw Conveyors 339
Hopper Truck and Car Loading 340
Air Pollution Control Equipment 340
ROCK AND GRAVEL AGGREGATE PLANTS 340
The Air Pollution Problem 340
Hooding and Ventilation Requirements 341
Air Pollution Control Equipment 341
Hooding and Ventilation Requirements 341
Air Pollution Control Equipment 341
MINERAL WOOL FURNACES 341
Introduction 342
Types and Uses of Mineral Wool Products 342
Mineral Wool Production 342
The Air Pollution Problem 342
Hooding and Ventilation Requirements 343
Air Pollution Control Equipment 344
Baghouse Collection and Cupola Air Contaminants 347
Afterburner Control of Curing Oven Air Contaminants 347
Reducing Blowchamber Emissions 347
Controlling Asphalt Fumes 349
PERLITE-EXPANDING FURNACES 349
Introduction 350
Uses 350
Mining Sites 350
Perlite Expansion Plants 350
Expansion Furnaces 350
Gas and Product Cooling 350
Product Collectors and Classifiers. 350
The Air Pollution Problem 350
Hooding and Ventilation Requirements 351
Air Pollution Control Equipment 351
FEED AND GRAIN MILLS 351
Introduction 352
Receiving, Handling, and Storing Operations 352
Feed-Manufacturing Processes 353
The Air Pollution Problem 354
Receiving, Handling, and Storing Operations 355
356

Feed-Manufacturing Processes 357
Hooding and Ventilation Requirements 357
Receiving, Handling, and Storing Operations 357
Feed-Manufacturing Processes 358
Air Pollution Control Equipment 358
Receiving, Handling, and Storing Operations 359
Feed-Manufacturing Processes 359
Filter Vents 359
Cyclones 359
Baghouses 360
PNEUMATIC CONVEYING EQUIPMENT 362
Introduction 362
Types of Pneumatic Conveying Systems 362
Types of Air-Moving Used in Conveying 363
Preliminary Design Calculations 365
The Air Pollution Problem 367
Air Pollution Control Equipment 367
DRIERS 367
Introduction 367
Rotary Driers 367
Flash Driers 368
Spray Driers 369
Other Types of Driers 370
The Air Pollution Problem 371
Hooding and Ventilation Requirements 371
Air Pollution Control Equipment 371
Dust Control 371
Drying With Solvent Recovery 371
Smoke and Odor Emissions 372
WOODWORKING EQUIPMENT 372
Exhaust Systems 372
Construction of Exhaust Systems 372
The Air Pollution Problem 373
Hooding and Ventilation Requirements 373
Air Pollution Control Equipment 373
Disposal of Collected Wastes 374
RUBBER-COMPOUNDING EQUIPMENT 375
Introduction 375
Additives Employed in Rubber Compounding 375
The Air Pollution Problem 376
Hooding and Ventilation Requirements 377
Air Pollution Control Equipment 377
ASPHALT ROOFING FELT SATURATORS 378
Description and Operation 378
The Air Pollution Problem 378
Hooding and Ventilation Requirements 378
Air Pollution Control Equipment 378
Low-Voltage Electrical Precipitators 378
Design Considerations for Electrical Precipitators 379
Maintenance of Precipitators 381
Baghouses 382
Scrubbers 382
SOLVENT DEGREASERS 383
Introduction 383
Design and Operation 383
Types of Solvent 383
The Air Pollution Problem 383
Solvent Losses 383
Hooding and Ventilation Requirements 384
Air Pollution Control Equipment 384
Methods of Minimizing Solvent Emissions 384

Tank Covers
Controlling Vaporized Solvent . . . 385
SURFACE-COATING OPERATIONS . . . 385
Introduction . . . 387
Spray Booths . . . 387
Flowcoating Machines . . . 388
Paint Dip Tanks . . . 388
Roller Coating Machines . . . 388
The Air Pollution Problem . . . 389
Air Contaminants From Paint Spray Booths . . . 389
Air Contaminants From Other Devices . . . 389
Hooding and Ventilation Requirements . . . 389
Requirements for Paint Spray Booths . . . 389
Requirements for Other Devices . . . 389
Air Pollution Control Equipment . . . 389
Control of Paint Spray Booth Particulates . . . 389
Control of Organic Vapors From Surface Coatings . . . 389
PIPE-COATING EQUIPMENT . . . 390
Introduction . . . 390
Methods of Application . . . 390
Pipe Dipping . . . 390
Pipe Spinning . . . 390
Pipe Wrapping . . . 390
Preparation of enamel - 391
The Air Pollution Problem . . . 391
Hooding and Ventilation Requirements . . . 391
Air Pollution Control Equipment . . . 391
DRY CLEANING EQUIPMENT . . . 393
The Air Pollution Problem . . . 393
Solvents . . . 395
Lint . . . 395
Hooding and Ventilation Requirements . . . 396
Air Pollution Control Equipment . . . 396
ABRASIVE BLAST CLEANING . . . 396
Introduction . . . 397
Abrasive Materials . . . 397
Method of Propelling the Abrasive . . . 397
Equipment Used to Confine the Blast . . . 397
The Air Pollution Problem . . . 398
Hooding and Ventilation Requirements . . . 399
Air Pollution Control Equipment . . . 400
ZINC-GALVANIZING EQUIPMENT . . . 400
Introduction . . . 401
Cleaning . . . 401
Cover Fluxes . . . 401
Foaming Agents . . . 402
Dusting Fluxes . . . 402
The Air Pollution Problem . . . 402
Physical and Chemical Composition of the Contaminants . . . 403
Hooding and Ventilation Requirements . . . 403
Air Pollution Control Equipment . . . 404
Baghouses . . . 405
Electrical Precipitators . . . 406
408

CHAPTER 8. INCINERATION

DESIGN PRINCIPLES FOR MULTIPLE-CHAMBER INCINERATORS . . . 413
Retort Type . . . 413
In-Line Type . . . 413
Description of the Process . . . 415
Design Types and Limitations . . . 416
Comparison of Types . . . 416

Principles of Combustion 416
Design Factors 416
Design Precepts 417
GENERAL-REFUSE INCINERATORS 417
The Air Pollution Problem 419
Air Pollution Control Equipment 420
Design Procedure 420
General Construction 421
Refractories 422
Grates and Hearths 423
Air Inlets 423
Stack 423
Induced-Draft System 425
Operation 426
Illustrative Problem 426
MOBILE MULTIPLE-CHAMBER INCINERATORS 426
Design Procedure 428
Stack Requirements 428
Induced-Draft Fan System 428
Standards of Construction 428
Refractories 430
Grates 430
Air Inlets 430
Structure 430
Auxiliary Burners 430
Stack Emissions 430
Illustrative Problem 430
MULTIPLE-CHAMBER INCINERATORS FOR BURNING WOOD WASTE 431
Introduction 436
Description of the Refuse 436
The Air Pollution Problem 436
Air Pollution Control Equipment 436
Design Procedure 436
Incinerator Arrangements 436
Design Procedure for Mechanical Feed Systems 439
Surge Bin 441
Screw or Drag Conveying 441
Pneumatic Conveying 442
Standards for Construction 443
Refractories 443
Grates 444
Exterior Walls 444
Air Ports 444
Operation of Incinerators 444
Illustrative Problem 445
FLUE-FED APARTMENT INCINERATORS 445
Introduction 447
Description of Refuse 447
The Air Pollution Problem 448
Stack Emissions 448
Air Pollution Control Equipment 448
Installation of Afterburner on a Roof 448
Design Procedure 449
Draft control - 449. . . Chute door locks - 450 . . Design parameters - 450. . .
Limitations - 450. . . Typical installations - 451
Standards for Construction 452
Mounting and supports - 452 . . Metals - 452. . . Castable refractories - 452 . . .
Firebrick - 452. . . Insulating firebrick - 452. . . Burners - 452 . . .
Draft control damper - 453 . . . Chute door locks - 453
Stack Emissions 453
Operation 453

Basement Afterburner
Design Procedure . . . 454
Design parameters - 454. . . Typical installation . . . 454
Standards for Construction
Hot-zone refractory - 455 . . . Draft control damper - 455 . . . 455
Stack Emissions
Operation . . . 455
Multiple-Chamber Incinerator, Basement Installation . . . 455
Design Procedure . . . 455
Draft control - 456. . . Typical installation - 456 . . . 455
Standards for Construction
Stack Emissions . . . 457
Operation . . . 457
Illustrative Problem . . . 457
PATHOLOGICAL-WASTE INCINERATORS . . . 457
The Air Pollution Problem . . . 460
Air Pollution Control Equipment . . . 461
Design Procedure . . . 461
Ignition chamber - 463 . . . Secondary combustion zone - 463 . . . Stack design - 463. . .
Crematory design - 464 . . Incinerator design configuration - 464 . . . 461
Standards for Construction
Stack Emissions . . . 465
Operation . . . 466
Illustrative Problem . . . 466
DEBONDING OF BRAKE SHOES AND RECLAMATION OF ELECTRICAL EQUIPMENT WINDINGS . . . 468
Debonding of Brake Shoes . . . 471
Reclamation of Electrical Equipment Winding . . . 471
The Air Pollution Problem . . . 472
Air Pollution Control Equipment . . . 472
Primary Ignition Chamber . . . 473
Secondary Combustion Chamber . . . 473
Stack . . . 474
Emissions . . . 474
Typical Reclamation Equipment . . . 474
Standards for Construction . . . 474
Illustrative Problem . . . 476
DRUM RECLAMATION FURNACES . . . 476
Introduction . . . 481
Description of the Furnace Charge . . . 481
Description of the Process . . . 482
The Air Pollution Problem . . . 482
Air Pollution Control Equipment . . . 482
Primary Ignition Chamber, Batch Type . . . 482
Primary Ignition Chamber, Continuous Type . . . 482
Afterburner (Secondary Combustion Chamber) . . . 483
Draft . . . 486
Standards for Construction . . . 486
Operation . . . 486
Illustrative Problem . . . 487
WIRE RECLAMATION . . . 487
Description of the Process . . . 495
Description of the Charge . . . 495
The Air Pollution Problem . . . 496
Air Pollution Control Equipment . . . 496
Primary Ignition Chamber . . . 496
Secondary Combustion . . . 496
Emissions . . . 497
Draft . . . 497
Equipment Arrangement . . . 498
General Construction . . . 498
. . . 499

Refractories 499
Charge Door 499
Combustion Air Ports 500
Gas Burners 500
Operation 500
Illustrative Problem 500

CHAPTER 9. COMBUSTION EQUIPMENT

GASEOUS AND LIQUID FUELS 507
Introduction 507
Gaseous Fuels 507
Oil Fuels 508
The Air Pollution Problem 509
Black Smoke 509
White Smoke 509
Particulate Emissions 510
Sulfur in Fuels 510
Sulfur Oxides 511
Oxides of Nitrogen 511
Air Pollution Control Methods 511
Prohibitions Against Sulfur Emissions 511
Removal of Sulfur and Ash From Fuels 512
Illustrative Problem 512
GAS AND OIL BURNERS 514
Introduction 514
Draft Requirements 514
Gas Burners 514
Partially Aerated Burners 515
Multiple-Port Gas Burners 516
Forced-Draft Gas Burners 516
Gas Flow Rates 517
Oil Burners 517
Viscosity and Oil Preheaters 520
The Air Pollution Problem 521
Smoke and Unburned Contaminants 521
Ash and Sulfur Oxides 525
Oxides of Nitrogen 525
Air Pollution Control Equipment 525
BOILERS, HEATERS, AND STEAM GENERATORS 525
Introduction 525
Industrial Boilers and Water Heaters 525
Power Plant Steam Generators 526
Refinery Heaters 528
Hot Oil Heaters and Boilers 528
Fireboxes 529
Soot Blowing 531
The Air Pollution Problem 532
Solid Particulate Emission During Normal Oil Firing 534
Soot-Blowing Particulates 535
Sulfur Dioxide 535
Sulfur Trioxide 536
Excessive Visible Emissions 537
Oxides of Nitrogen 539
Estimating NO_x Emissions 542
Air Pollution Control Equipment 543
Sulfur Compounds 544
Combustible Particulates 544
Soot Collectors 544
Sulfur Oxides Collection 545
Scrubbers for Sulfur Oxides 545
Baghouses and Precipitators 547

Alkaline Additives to Neutralize Sulfur Trioxide 548
Other Metal Oxides for Sulfur Dioxide Removal 549
Baghouses With Dolomite Addition for Sulfur Trioxide Removal 549
Electrical Precipitators With Additives 552
Carbon Adsorption of Sulfur Oxides 552
Oxidation of Sulfur Dioxide 553
Inhibiting Sulfur Trioxide Formation at Reduced Oxygen 553
Controlling Oxides of Nitrogen 554
Two-Stage Combustion 554
Corner-Fired Steam Generators 555
Lowering Excess Air 556
Eliminating Air Preheat 556
Other Means of Lowering Flame Temperature 557
Catalytic Decomposition of NO_x 557
Scrubbing NO_x 558
Adsorption of NO_x 558

CHAPTER 10. PETROLEUM EQUIPMENT

GENERAL INTRODUCTION 561
Crude Oil Production 561
Refining 561
Flares and Blowdown Systems 561
Pressure Relief Valves 561
Storage Vessels 561
Bulk-Loading Facilities 562
Catalyst Regenerators 562
Effluent-Waste Disposal 564
Pumps and Compressors 564
Air-Blowing Operations 564
Pipeline Valves and Flanges, Blind Changing, Process Drains 564
Cooling Towers 564
Vacuum Jets and Barometric Condensers 564
Effective Air Pollution Control Measures 565
Marketing 565
WASTE-GAS DISPOSAL SYSTEMS 565
Introduction 565
Design of Pressure Relief System 568
Safety Valves 569
Rupture Discs 570
Sizing rupture discs - 572 . . . Sizing liquid safety valves - 573 . . .
Sizing vapor and gas relief and safety valves - 574 . . .
Installing relief and safety valves and rupture discs - 575 . . . Knockout vessels - 576 . . .
Sizing a blowdown line - 578
The Air Pollution Problem 584
Smoke From Flares 584
Other Air Contaminants From Flares 584
Air Pollution Control Equipment 585
Types of Flares 585
Elevated flares - 585 . . . Ground level flares - 589 . . . Effect of steam injection - 593 . . .
Design of a smokeless flare - 593 . . . Pilot ignition system - 595 . . .
Instrumentation and control of steam and gas - 596 . . . Supply and control of steam - 598 . .
Design of water-injection-type ground flares - 603 . . .
Design of venturi-type ground flares - 604 . . . Maintenance of flares - 606
STORAGE VESSELS 606
Types of Storage Vessels 606
Pressure Tanks and Fixed-Roof Tanks 606
Floating-Roof Tanks 607
Conservation Tanks 608
Open-Top Tanks, Reservoirs, Pits, and Ponds 611
The Air Pollution Problem 611
Factors Affecting Hydrocarbon Vapor Emissions 611

Hydrocarbon Emissions From Floating-Roof Tanks 612
Withdrawal emissions - 614 . . Application of results - 614
Hydrocarbon Emissions From Low-Pressure Tanks 614
Hydrocarbon Emissions From Fixed-Roof Tanks 618
Aerosol Emissions 622
Odors 622
Air Pollution Control Equipment 623
Seals for Floating-Roof Tanks 624
Floating Plastic Blankets 624
Plastic Microspheres 625
Vapor Balance Systems 627
Vapor Recovery Systems 627
Miscellaneous Control Measures 628
Masking Agents 629
Costs of Storage Vessels 629
LOADING FACILITIES 629
Introduction 629
Loading Racks 632
Marine Terminals 632
Loading Arm Assemblies 632
The Air Pollution Problem 633
Air Pollution Control Equipment 635
Types of Vapor Collection Devices for Overhead Loading 635
Collection of Vapors From Bottom Loading 638
Factors Affecting Design of Vapor Collection Apparatus 639
Methods of Vapor Disposal 640
CATALYST REGENERATION 642
Types of Catalysts 642
Loss of Catalyst Activity 644
Regeneration Processes 644
FCC Catalyst Regenerators 644
TCC Catalyst Regenerators 645
Catalyst Regeneration in Catalytic Reformer Units 645
The Air Pollution Problem 646
Air Pollution Control Equipment 647
Wet- and Dry-Type, Centrifugal Dust Collectors 647
Electrical Precipitators 648
Carbon Monoxide Waste-Heat Boilers 650
Economic Considerations 651
OIL-WATER EFFLUENT SYSTEMS 652
Functions of Systems 652
Handling of Crude-Oil Production Effluents 652
Handling of Refinery Effluents 653
Treatment of Effluents by Oil-Water Separators 653
Clarification of Final-Effluent Water Streams 653
Effluent Wastes From Marketing Operations 654
The Air Pollution Problem 654
Air Pollution Control Equipment 655
Hydrocarbons From Oil-Water Separators 655
Treatment of Refinery Liquid Wastes at Their Source 657
Oil-in-water emulsions - 657. . . Sulfur-bearing waters - 657. . . Acid sludge - 658 . . .
Spent caustic wastes - 659
PUMPS 659
Types of Pumps 659
Positive-Displacement Pumps 660
Centrifugal Pumps 660
The Air Pollution Problem 661
Air Pollution Control Equipment 661
Results of Study to Measure Losses From Pumps 664
AIRBLOWN ASPHALT 665
Recovery of Asphalt From Crude Oil 666

Airblowing of Asphalt 666
The Air Pollution Problem 667
Air Pollution Control Equipment 667
VALVES 669
Types of Valves 669
Manual and Automatic Flow Control Valves 669
Pressure Relief and Safety Valves 670
The Air Pollution Problem 670
Total Emissions From Valves 671
Air Pollution Control Equipment 671
COOLING TOWERS 672
Characteristics of Cooling Tower Operation 673
The Air Pollution Problem 674
Air Pollution Control Equipment 675
MISCELLANEOUS SOURCES 675
Airblowing 675
Blind Changing 675
Equipment Turnarounds 676
Tank Cleaning 677
Use of Vacuum Jets 677
Use of Compressor Engine Exhausts 677

CHAPTER 11. CHEMICAL PROCESSING EQUIPMENT

RESIN KETTLES 681
Types of Resins 681
Phenolic Resins 681
Amino Resins 682
Polyester and Alkyd Resins 682
Polyurethane 683
Thermoplastic Resins 683
Polyvinyl Resins 683
Polystyrene 684
Petroleum and Coal Tar Resins 684
Resin-Manufacturing Equipment 684
The Air Pollution Problem 685
Air Pollution Control Equipment 686
VARNISH COOKERS 688
Introduction 688
Raw Materials for Varnish Making 689
Major Types of Manufacturing Equipment 690
Variations in Varnish Formulation 691
The Air Pollution Problem 691
Hooding and Ventilation Requirements 692
Air Pollution Control Equipment 692
Scrubbers 692
Adsorbers 693
Afterburners 693
SULFURIC ACID MANUFACTURING 695
Contact Process 695
The Air Pollution Problem 697
Air Pollution Control Equipment 698
Sulfur Dioxide Removal 698
Acid Mist Removal 698
Electrical precipitators - 698 . . . Packed-bed separators - 699 . . .
Wire mesh mist eliminators - 700 . . . Ceramic filters - 700 . . Sonic agglomeration - 701 . .
Miscellaneous devices - 701
PHOSPHORIC ACID MANUFACTURING 701
Phosphoric Acid Process 701
The Air Pollution Problem 702
Hooding and Ventilation Requirements 702
Air Pollution Control Equipment 703

PAINT-BAKING OVENS 704
Bake Oven Equipment 705
The Air Pollution Problem 706
Hooding and Ventilation Requirements 707
Air Pollution Control Equipment 708
Cost of Direct-Flame Afterburners 708
Illustrative Problem 708
SOAPS AND SYNTHETIC DETERGENTS 716
Soaps 716
Raw Materials 716
Fatty Acid Production 716
Soap Manufacture 717
Soap Finishing 717
Synthetic Detergents 718
The Air Pollution Problem 718
Soaps 718
Detergents 719
Air Pollution Control Equipment 719
Soaps 719
Detergents 720
GLASS MANUFACTURE 720
Types of Glass 720
Glass-Manufacturing Process 721
Handling, Mixing, and Storage Systems for Raw Materials 722
The Air Pollution Problem 723
Hooding and Ventilation Requirements 723
Air Pollution Control Equipment 724
Glass-Melting Furnaces 724
Continuous Soda-Lime Glass Furnaces 724
The Air Pollution Problem 726
Source test data - 727 . . .Opacity of stack emissions - 727
Hooding and Ventilation Requirements 728
Air Pollution Control Methods 729
Control of raw materials - 731 . . Batch preparation - 732 . . .Checkers - 732 . . .
Preheaters - 733 . . Refractories and insulation - 733 . . Combustion of fuel - 734 . . .
Electric melting - 735. . . Baghouses and centrifugal scrubbers - 735
Glass-Forming Machines 736
The Air Pollution Problem 737
Air Pollution Control Methods 737
FRIT SMELTERS 738
Introduction 738
Raw Materials 738
Types of Smelters 738
Frit Manufacturing 740
Application, Firing, and Uses of Enamels 742
The Air Pollution Problem 743
Hooding and Ventilation Requirements 743
Air Pollution Control Equipment 744
FOOD PROCESSING EQUIPMENT 746
Coffee Processing 746
Batch Roasting 747
An Integrated Coffee Plant 747
The Air Pollution Problem 747
Hooding and Ventilation Requirements 749
Air Pollution Control Equipment 749
Smokehouses 750
The Smoking Process 750
Atmospheric Smokehouses 750
Recirculating Smokehouses 750
The Air Pollution Problem 751
Hooding and Ventilation Requirements 751

Bypassing control devices during nonsmoking periods - 752
Air Pollution Control Equipment 752
Afterburners - 752 . . Electrical precipitators - 752 . . Electrical precipitation versus incineration - 753 . . . Why not immersion? - 754 . . . Smoking through electrical precipitation - 754
Deep Fat Frying 755
Batch or Continuous Operation 755
The Air Pollution Problem 756
Hooding and Ventilation Requirements 756
Air Pollution Control Equipment 756
Oil collection - 757
Livestock Slaughtering 757
The Air Pollution Problem 757
Air Pollution Control Equipment 757
Edible-Lard and Tallow Rendering 758
Dry Rendering 759
Low-Temperature, Continuous Rendering 759
Wet Rendering 759
The Air Pollution Problem 760
Hooding and Ventilation Requirements 760
Air Pollution Control Equipment 760
FISH CANNERIES AND FISH REDUCTION PLANTS 760
Wet-Fish Canning 761
Tuna Canning 761
Cannery Byproducts 762
Fish Meal Production 762
Fish Solubles and Fish Oil Production 763
Digestion Processes 765
The Air Pollution Problem 765
Odors From Meal Driers 765
Smoke From Driers 766
Dust From Driers and Conveyors 766
Odors From Reduction Cookers 766
Odors From Digesters 767
Odors From Evaporators 767
Odors From Edibles Cookers 767
Hooding and Ventilation Requirements 767
Air Pollution Control Equipment 768
Controlling Fish Meal Driers 768
Incinerating Drier Gases 768
Chlorinating and Scrubbing Drier Gases 768
Controlling Reduction Cookers 770
Controlling Digesters 770
Controlling Evaporators 770
Collecting Dust 770
Controlling Edible-Fish Cookers 770
REDUCTION OF INEDIBLE ANIMAL MATTER 770
Dry Rendering 772
Wet Rendering 773
Refining Rendered Products 773
Drying Blood 775
Processing Feathers 775
Rotary Air Driers 775
The Air Pollution Problem 776
Cookers as Prominent Odor Sources 777
Odors From Air Driers 777
Odors and Dust From Rendered-Product Systems 778
Grease-Processing Odors 778
Raw-Materials Odors 778
Hooding and Ventilation Requirements 778
Emission Rates From Cookers 778
Emission Rates From Driers 779

Air Pollution Control Equipment 780
Controlling High-Moisture Streams 780
Subcooling Condensate 780
Condenser Tube Materials 781
Interceptors in Cooker Vent Lines 781
Vapor Incinerator 781
Condensation-Incineration Systems 782
Carbon Adsorption of Odors 783
Odor Scrubbers 783
Odor Masking and Counteraction 784
ELECTROPLATING 784
The Air Pollution Problem 785
Hooding and Ventilating Requirements 785
Air Pollution Control Equipment 786
Scrubbers 786
Mist Inhibitors 787
INSECTICIDE MANUFACTURE 787
Methods of Production 787
Solid-Insecticide Production Methods 787
Liquid-Insecticide Production Methods 791
The Air Pollution Problem 791
Hooding and Ventilation Requirements 791
Air Pollution Control Equipment 791
HAZARDOUS RADIOACTIVE MATERIAL 792
Hazards in the Handling of Radioisotopes 792
The Air Pollution Problem 793
Characteristics of Solid, Radioactive Waste 793
Characteristics of Liquid, Radioactive Waste 793
Problems in Control of Airborne, Radioactive Waste 794
Hooding and Ventilation Requirements 794
Hooding 794
Ventilation 794
Air Pollution Control Equipment 794
Reduction of Radioactive, Particulate Matter at Source 794
Design of Suitable Air-Cleaning Equipment 795
Reverse-jet baghouse - 796 . . Wet collectors - 796 . . Electrical precipitators - 796 . . .
Glass fiber filters - 797 . . . Paper filters - 797
Disposal and Control of Solid, Radioactive Waste 798
Disposal and Control of Liquid, Radioactive Waste 798
OIL AND SOLVENT RE-REFINING 799
Re-refining Process for Oils 799
Re-refining Process for Organic Solvents 800
The Air Pollution Problem 800
Air Pollution From Oil Re-refining 800
Air Pollution From Solvent Re-refining 800
Air Pollution Control Equipment 800
Oil Re-refining 800
Solvent Re-refining 801
CHEMICAL MILLING 801
Description of the Process 801
Etchant Solutions 802
The Air Pollution Problem 802
Mists 803
Vapors 804
Gases 804
Solvents 804
Hooding and Ventilation Requirements 804
Air Pollution Control Equipment 804
Corrosion Problems 805
REFERENCES 807

APPENDIX A: RULES AND REGULATIONS 831
Rules and Regulations of the Air Pollution Control District 831
APPENDIX B: ODOR-TESTING TECHNIQUES 861
The Odor Panel 861
The Odor Evaluation Room 861
Sampling Techniques 862
Evaluation of Odor Samples 863
Determination of Odor Concentration 864
APPENDIX C: HYPOTHETICAL AVAILABLE HEATS FROM NATURAL GAS 867
APPENDIX D: MISCELLANEOUS DATA 871

CHAPTER 1

INTRODUCTION

JOHN A. DANIELSON, Senior Air Pollution Engineer

ROBERT L. CHASS, Chief Deputy Air Pollution Control Officer

ROBERT G. LUNCHE, Director of Engineering

CHAPTER 1

INTRODUCTION

The past two decades have witnessed remarkable progress in the development of reasonable engineering solutions for controlling industrial and commercial sources of air pollution. This manual presents the practical technical knowledge acquired through nearly 20 years of experience by the Engineering Division of the Los Angeles County Air Pollution Control District. With the rich background of experience attained by government and industry, this engineering knowledge can now be applied to solving specific community air pollution problems throughout the world.

THE LOS ANGELES BASIN

Los Angeles and its environs have special problems peculiar to the area. Los Angeles County is the largest heavily industrialized, semitropical area in the world. It comprises 4,083 square miles and contains more than 75 incorporated cities and large scattered unincorporated areas. Its population has more than doubled since 1939, and industry has expanded from approximately 6,000 establishments in 1939 to more than 17,000 in 1963 (Weisburd, 1962).

Topographical and meteorological conditions aggravate the effects of the pollution produced by this population and this industry in the Los Angeles Basin. The average wind velocity there is less than 6 miles per hour. The light winds that do develop are relatively ineffective in carrying off the polluted air because of the temperature inversions that prevail approximately 260 days of the year. The height of the inversion base varies from ground level to 3,000 feet. These inversions have been most noticeable during the summer months, but in the last few years extreme inversions have occurred in the November-December period as well. Their effect is to limit vertical distribution of atmospheric pollution while local winds from the west are moving the air over the area during the day.

In Los Angeles County, the complex mixture of smoke, dusts, fumes, gases, and other solid and liquid particles is called "smog." This smog may produce a single effect or a combination of effects, such as irritation of eyes, irritation of throats, reduction of visibility, damage to vegetation, cracking of rubber, local nuisances, and a host of other effects, real and fancied.

Any community suffering from an air pollution problem must inevitably turn its attention to the operations of industry, because these operations have been most frequently associated with community air pollution problems. Accordingly, the Los Angeles County control program was first directed to industrial operations.

Although the exact year when smog was first recognized in Los Angeles is not known, the first public demands for relief from air pollution appear to have been made immediately after World War II (Weisburd, 1962). Newspapers, in particular, began to expose the problem in the public interest. As a consequence, air pollution control groups were formed under health department jurisdiction--first by the city of Los Angeles, and then by the county of Los Angeles in the unincorporated areas. These control efforts failed, however, because of the multiplicity and inadequacy of the control jurisdictions. It was soon apparent that adequate control could be exercised only by a single authority with jurisdiction over the entire pollution zone--the incorporated and unincorporated areas of Los Angeles County. As a result, Assembly Bill No. 1 was presented to the 1947 session of the California Legislature. This Bill proposed consolidation of control measures. The Legislature voted to add Chapter 2, "Air Pollution Control District," to Division 20 of the Health and Safety Code relating to the control and suppression of air pollution. Thus, the first statewide air pollution control statute was enacted. This statute, The California Act, is an enabling type of legislation that legalizes the establishment of air pollution control districts on a local option basis by the counties of California.

RULES AND REGULATIONS IN LOS ANGELES COUNTY

Under authority of the Health and Safety Code, the Board of Supervisors of Los Angeles County enacted, on December 30, 1947, the first rules and regulations guiding the conduct of the Los Angeles County Air Pollution Control District. Additional rules and regulations were enacted as the need arose. The rules are contained in seven regulations, as follows: (I) "General Provisions," (II) "Permits," (III) "Fees," (IV) "Prohibitions," (V) "Procedure Before the Hearing Board," (VI) "Orchard Heaters," (VII) "Emergencies."

The rules and regulations are extensive and are shown in Appendix A for those desiring detailed

information. In using this manual, the reader should be aware of certain provisions of these statutes, and these will be summarized in this chapter. Of most importance to the reader are Regulations II "Permits" and IV "Prohibitions."

REGULATION II: PERMITS

The permit system of the Los Angeles County Air Pollution Control District is one of the most important features of the air pollution control program. A diagram of the permit system and how it operates is given in Figure 1. In general, the system requires owners, operators, or lessees to apply for permits to construct and operate any equipment capable of emitting air contaminants. If the applicant's plans, specifications, and field tests show that the equipment can operate within the limits allowed by law, then a permit is granted. If the equipment is capable of emitting contaminants that create a public nuisance or violate any section of the State Health or Safety Code or the rules and regulations of the Air Pollution Control District, then a permit is denied.

This permit system is effective because it eliminates use of equipment that emits excessive air contaminants or reduces emissions to within allowable limits by requiring that the design of the equipment or of the process be modified or that adequate control equipment be used. The construction or operation of control equipment must also be authorized by permit. Thus, the permit system is a positive means of controlling air pollution.

In using this regulation, the members of the Engineering Division of the Air Pollution Control District have reviewed the design and approved or denied the construction or operation of thousands of industrial and commercial enterprises in Los Angeles County. These 15 years of experience provide the background for much of the data in this manual.

REGULATION IV: PROHIBITIONS

The rules in Regulation IV prohibit the emission of certain air contaminants and regulate certain types of equipment. Because these rules apply to engineering problems and touch upon many sciences, they require extraordinary care for their framing. The prohibitions pertinent to readers of this manual will now be discussed.

Rule 50: The Ringelman Chart

Rule 50 sets standards for reading densities and opacities of visible emissions in determining violation of, or compliance with, the law. It limits to 3 minutes in any hour the discharge, from any single source, of any air contaminant that is (1) as dark as or darker than that designated as Number 2 on the Ringelmann Chart, or (2) of such opacity as to obscure an observer's view to a degree equal to or greater than that to which smoke described in (1) does.

Rule 51: Nuisance

According to Rule 51, whatever tends to endanger life or property or whatever effects the health of the community is a public nuisance. The nuisance must, however, affect the community at large and not merely one or a few persons. A nuisance becomes a crime if it contributes seriously to the discomfort of an area.

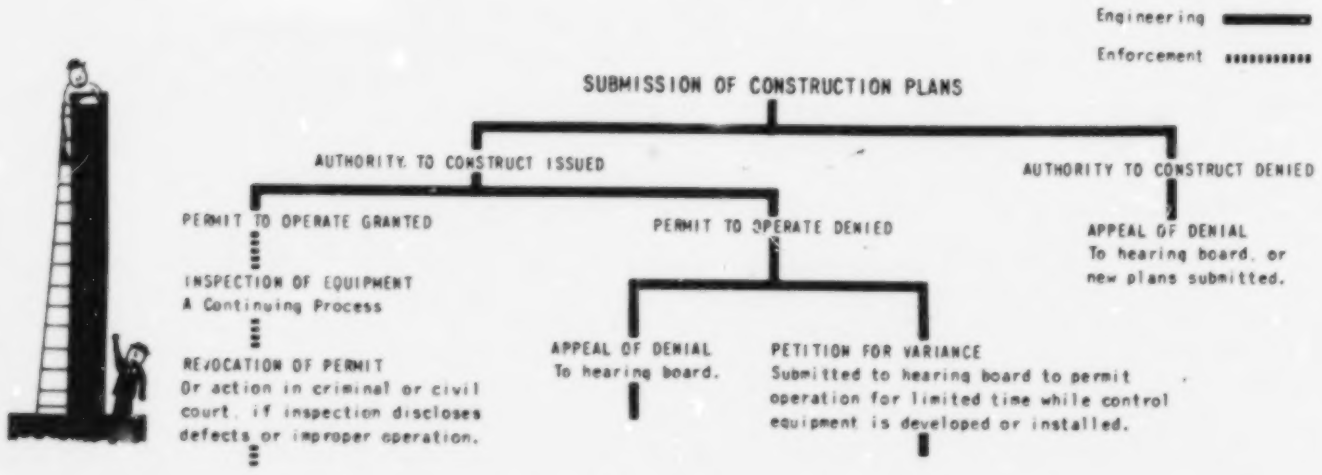

Engineering
Enforcement
SUBMISSION OF CONSTRUCTION PLANS
AUTHORITY TO CONSTRUCT ISSUED
AUTHORITY TO CONSTRUCT DENIED
PERMIT TO OPERATE GRANTED
PERMIT TO OPERATE DENIED
APPEAL OF DENIAL
To hearing board, or new plans submitted.
INSPECTION OF EQUIPMENT
A Continuing Process
REVOCATION OF PERMIT
Or action in criminal or civil court, if inspection discloses defects or improper operation.
APPEAL OF DENIAL
To hearing board.
PETITION FOR VARIANCE
Submitted to hearing board to permit operation for limited time while control equipment is developed or installed.

Figure 1. The permit system and how it operates when industry seeks to install equipment that may pollute the air.

Rule 52: Particulate Matter

Rule 52 establishes the maximum allowable limits for the discharge of particulate matter. It limits the discharge of this contaminant from any source to a maximum concentration of 0.4 grain per cubic foot of gas at standard conditions of 60° F and 14.7 psia. This rule does not, however, apply when the particulate matter is a combustion contaminant.*

Rule 53: Specific Contaminants

Rule 53 establishes the maximum allowable limits for the discharge of sulfur compounds and combustion contaminants as follows:

Rule 53a: Sulfur compounds calculated as sulfur dioxide (SO_2): 0.2 percent, by volume.

Rule 53b: Combustion contaminants: 0.3 grain per cubic foot of gas calculated to 12 percent of carbon dioxide (CO_2) at standard conditions. In measuring the combustion contaminants from incinerators used to dispose of combustible refuse by burning, the CO_2 produced by combustion of any liquid or gaseous fuels shall be excluded from the calculation to 12 percent of CO_2.

Rule 53.1: Scavenger Plants

Rule 53.1 sets forth the conditions under which a scavenger or recovery plant may operate under permit. These plants are built in Los Angeles County to recover sulfur products, which might otherwise be emitted to the air.

Rule 54: Dust and Fumes

Rule 54 establishes the maximum allowable limits for the discharge of dusts and fumes according to the process weights† of materials processed per hour. The maximum allowable weight in pounds per hour is graduated according to the weights of materials processed per hour. The maximum emission allowed is 40 pounds per hour where 60,000 or more pounds are processed in the equipment in any given hour.

*Particulate matter is any material, except uncombined water, that exists in a finely divided form as a liquid or solid at standard conditions. A combustion contaminant is particulate matter discharged into the atmosphere from the burning of any kind of material containing carbon in a free or combined state.

†Process weight is the total weight of all materials introduced into any specific process that is capable of causing any discharge into the atmosphere. Solid fuels charged are considered part of the process weight, but liquid and gaseous fuels and combustion air are not. The "process weight per hour" is derived by dividing the total process weight by the number of hours in one complete operation from the beginning of any given process to the completion thereof, excluding any time during which the equipment is idle.

Rule 56: Storage of Petroleum Products

Rule 56 sets forth the type of equipment that can be used for the control of hydrocarbons arising from the storage of gasoline and certain petroleum distillates. Rule 56 provides that any tank of more than 40,000-gallon capacity used for storing gasoline or any petroleum distillate having a vapor pressure of 1-1/2 psia or greater must be equipped with a vapor loss control device such as a pontoon-type or double-deck-type floating roof or a vapor recovery system capable of collecting all emissions.

Rules 57 and 58: Open Fires and Incinerators

Rules 57 and 58 ban the burning of combustible refuse in open fires and single-chamber incinerators in the Los Angeles Basin.

Rule 59: Oil-Effluent Water Separators

Rule 59 regulates the type of equipment that can be used for the control of hydrocarbons from oil-water separators. It provides that this equipment must either be covered, or provided with a floating roof, or equipped with a vapor recovery system, or fitted with other equipment of equal efficiency if the effluent handled by the separator contains a minimum of 200 or more gallons of petroleum products per day.

Rule 61: Gasoline Loading Into Tank Trucks and Trailers and Trailers

Rule 61 sets forth the type of control equipment that can be used for the control of hydrocarbons resulting from the loading of gasoline into tank trucks. It provides for the installation of vapor collection and disposal systems on bulk gasoline-loading facilities where more than 20,000 gallons of gasoline are loaded per day and requires that the loading facilities be equipped with a vapor collection and disposal system. The disposal system employed must have a minimum recovery efficiency of 90 percent or a variable vapor space tank compressor and fuel gas system of such capacity as to handle all vapors and gases displaced from the trucks being loaded.

Rules 62 and 62.1: Sulfur Content of Fuels

Rules 62 and 62.1 prohibit the burning in the Los Angeles Basin of any gaseous fuel containing sulfur compounds in excess of 50 grains per 100 cubic feet of gaseous fuel (calculated as hydrogen sulfide

at standard conditions) or any liquid or solid fuel having a sulfur content in excess of 0.5 percent by weight, except when natural gas or low-sulfur fuels are not available.

Rule 63: Gasoline Specifications

Rule 63 prohibits the sale and use of fuel for motor vehicles having a degree of unsaturation exceeding a bromine number of 30.

Rule 64: Reduction of Animal Matter

Rule 64 requires that malodors from all equipment used for reduction of animal matter either be incinerated at temperatures of not less than 1,200°F for a period of not less than 0.3 second or processed in an odor-free manner under conditions stated in the rule.

Rule 65* Gasoline Loading into Tanks

Rule 65 prohibits the loading of gasoline into any stationary tank with a capacity of 250 gallons or more from any tank truck or trailer, except through a permanent submerged fill pipe, unless such tank is equipped with a vapor loss control device as described in Rule 56, or is a pressure tank as described in Rule 56.

Rule 66* Organic Solvents

Rule 66 requires that photochemically reactive organic solvent emissions in excess of 40 pounds per day (or 15 pounds per day from processes involving contact with a flame or baking, heat-curing or heat polymerizing, in the presence of oxygen) shall not be emitted unless controlled by incineration, adsorption, or in an equally efficient manner.

Rule 66.1: Architectural Coatings

Rule 66.1 prohibits the sale of architectural coatings containing photochemically reactive solvents in containers larger than 1-quart capacity. It also prohibits diluting any architectural coating with a photochemically reactive solvent.

*Rules 65 and 66 were adopted just prior to the publication of this manual. Consequently, control of equipment from sources involving these specific contaminants has not been discussed to the degree specified by these rules.

Rule 66.2: Disposal and Evaporation of Solvents

Rule 66.2 prohibits the disposal of more than 1-1/2 gallons per day of any photochemically reactive solvent by any means that will permit the evaporation of such solvent into the atmosphere.

ROLE OF THE AIR POLLUTION ENGINEER

Clearly, as indicated by this impressive list of prohibitions, the rules and regulations affect the operation of nearly every industry in Los Angeles County. Through their enforcement, controls have been applied to such diverse sources and operations as incinerators, open fires, rendering cookers, coffee roasters, petroleum refineries, chemical plants, rock crushers, and asphalt plants. From the smelting of metals to the painting of manufactured goods, industrial and commercial operations have been brought within the scope of the control program. This control has been accomplished through the use of the permit system.

ACCOMPLISHMENTS OF THE PERMIT SYSTEM

Under the permit system every source capable of emitting air contaminants and constructed since February 1948 has needed an authorization to be constructed and a permit to be operated from the Engineering Division of the Air Pollution Control District. From April 1948 through December 1963, 56,502 permits were issued by District engineers. The estimated value of the basic equipment was $651,447,000 and that of the control equipment was an additional $107,507,000. During this same period, 5,075 applications for basic and control equipment were denied.

This wealth of engineering experience is reflected in the contents of this manual. Nearly all the data presented were acquired through the experience and work of the District's Air Pollution engineers and of engineers in industry. Their pioneering efforts to stay at least one pace ahead of the problem have produced many engineering firsts in the control of air pollution.

USE OF THIS MANUAL

Users of this manual should remember that the degree of air pollution control discussed herein is based upon the prohibitions as set forth by the rules and regulations of the Los Angeles County Air Pollution Control District. In many areas, air pollution regulations are less stringent, and control devices of lower efficiency may be permitted.

GENERAL DESIGN PROBLEMS

This manual consists of 11 chapters and 4 appendixes. Chapters 2 through 5 present general design problems confronting air pollution engineers in the development of air pollution control systems. Specifically, chapter 2 describes the types of air contaminants encountered and chapter 3 presents design problems of hoods and exhaust systems. Types of control devices, and their general design features are discussed in chapters 4 and 5.

SPECIFIC AIR POLLUTION SOURCES

Chapters 6 through 11 discuss the control of air pollution from specific sources. Each solution of an air pollution problem represents a separate section of the text. Many processes are discussed: Metallurgical and mechanical processes, processes of incineration and combustion, and processes associated with petroleum and chemical equipment, each in a separate chapter and in that order. Usually the process is described and then the air pollution problem associated with it is discussed, together with the characteristics of the air contaminants and the unique design features of the air pollution control equipment.

By this arrangement, the reader can, if he wishes, refer only to that section discussing the specific process in which he is interested. If he wants to know more about the general design features of the air pollution control device serving that process, he can refer to chapters 4 and 5 on control equipment.

CHAPTER 2

AIR CONTAMINANTS

JANET DICKINSON, Senior Air Pollution Analyst

ROBERT L. CHASS, Chief Deputy Air Pollution Control Officer

W. J. HAMMING, Chief Air Pollution Analyst

CHAPTER 2

AIR CONTAMINANTS

INTRODUCTION

The purpose of this chapter is to describe briefly the parameters of an air pollution problem, particularly the problem of Los Angeles County; the measures taken to eliminate the problem; and those still needed. Other chapters will delineate, in detail, the methods and equipment successfully used in the control of emissions of air contaminants from a variety of stationary sources.

The control program in the County of Los Angeles during the past 15 years has been the most effective ever attempted anywhere. During the same period, however, the county has had a phenomenal population explosion that has caused the emissions from motor vehicles to overtake and surpass the gains made by control over stationary sources. The net effect has been the more frequent occurrence of smog symptoms over an increasingly larger area.

Since control over motor vehicle emissions is the responsibility of the state rather than of the local agency, substantial improvement in the situation in Los Angeles will probably have to await the successful accomplishment of the state's program. In the interim, however, the Air Pollution Control District of Los Angeles County will continue its efforts to reduce emissions of air contaminants from stationary sources wherever possible within its jurisdiction.

FACTORS IN AIR POLLUTION PROBLEMS

Literally, any substance not normally present in the atmosphere, or measured there in greater than normal concentrations, should be considered an air contaminant. More practically, however, a substance is not so labeled until its presence and concentration produce or contribute to the production of some deleterious effect.

Most foreign substances find their way into the atmosphere as the result of some human activity. Under normal circumstances, they diffuse throughout a rather large volume of air and do not accumulate to potentially harmful concentrations. Under less favorable conditions, however, the air volume available for this diffusion becomes inadequate and materials dispersed in it concentrate until an air pollution problem is created.

Air pollution problems may exist over a small area as a result of just one emission source or group of sources or they may be widespread and cover a whole community or urban complex involving a variety of sources. The effects that cause the situation to be regarded as a problem may be limited in scope and associated with a single kind of contaminant or they may be the variable results of complex atmospheric interaction of a number of contaminants.

The factors that contribute to the creation of an air pollution problem are both natural and man made. The natural factors are primarily meteorological, sometimes geographical, and are generally beyond man's sphere of control, whereas the manmade factors involve the emission of air contaminants in quantities sufficient to produce deleterious effects and are within man's sphere of control. The natural factors that restrict the normal dilution of contaminant emissions include: Temperature inversions, which prevent diffusion upwards; very low wind speeds, which do little to move emitted substances away from their points of origin; and geographical terrain, which causes the flow to follow certain patterns and carry from one area to another whatever the air contains. The manmade factors involve the contaminant emissions resulting from some human activity.

The predominant kind of air pollution problem involves simply the overloading of the atmosphere with harmful or unpleasant materials. This is the problem usually associated with an industrial area, and the type that has been responsible for all the killer air pollution incidents of the past. It is also the type of problem most readily solved, if the need and desire to do so are great enough. Contaminants frequently associated with this kind of problem include: Sulfur compounds (sulfur oxides, sulfates, sulfides, mercaptans); fluorides; metallic oxides; odors; smoke; and all types of dusts and fumes. The harmful effects may be such as to cause illness and death to persons and animals, damage to vegetation, or just annoyance and displeasure to persons in affected areas.

During the past 20 years, however, another kind of air pollution problem has evolved--that produced by the photochemical reaction of organic chemicals and oxides of nitrogen in the presence of sunlight. The effects of this type of air pollution were first noted in the Los Angeles area in the mid-1940's, but the cause was not then known,

nor was there any apparent relationship between the initial effects and air pollution.

The effect first noted was damage to vegetation. This was followed by irritation of the eyes, marked reduction in visibility not related to unusual quantities of atmospheric moisture or dust, and later, unexplained acceleration of the aging of rubber products as evidenced by cracking. Careful research over nearly 10 years demonstrated that all these effects were produced by the reaction in the atmosphere of organic compounds, principally hydrocarbons, and nitrogen dioxide, and that the cracking of rubber products was caused specifically by one of the products of these reactions, ozone.

Initially, only a relatively small portion of the Los Angeles Basin was affected, but a tremendous influx of new residents and new industrial growth during the past 15 years have caused a continuous enlargement of the affected area. Within this area, certain local problems related to single sources and groups of sources also exist, but they are of less significance than the overall problem of photochemical smog.

TYPES OF AIR CONTAMINANTS

Substances considered air contaminants in Los Angeles County fall into three classes on the basis of their chemical composition and physical state. These are (1) organic gases, (2) inorganic gases, and (3) aerosols. Each class may include many different compounds, emanate from several different sources, and contribute to the production of a number of characteristic smog effects. A brief summary of some of the contaminants, their principal sources, and their sign ficance is presented in Table 1.

ORGANIC GASES

The first group, organic gases, consists entirely of compounds of carbon and hydrogen and their derivatives. These include all classes of hydrocarbons (olefins, paraffins, and aromatics) and the compounds formed when some of the hydrogen in the original compounds is replaced by oxygen, halogens, nitro or other substituent groups. The latter are the hydrocarbon derivatives.

The principal origin of hydrocarbons is petroleum, and the principal sources of emissions of hydrocarbons and their derivatives are those related to the processing and use of petroleum and its products. Hydrocarbons are released to the atmosphere during the refining of petroleum, during the transfer and storage of petroleum products, and during the use of products such as fuels, lubricants, and solvents. Derivatives of hydrocarbons can also be released into the atmosphere in connection with these processes and in connection with their manufacture and use. They can even be formed in the atmosphere as the result of certain photochemical reactions.

Current Sources in Los Angeles County

More specifically, the principal current sources of organic gases in Los Angeles County are listed in Table 1.

Hydrocarbons

The most important source, by far, of emission of hydrocarbons is the use of gasoline for the operation of 3-1/2 million motor vehicles. This source alone accounts for approximately 1,930 tons per day, or 70 percent of the total emissions. Of this quantity, about 73 percent is attributed to exhaust emissions; 10 percent, to crankcase emissions; and 17 percent, to evaporation of fuel from carburetors and gasoline tanks. Except for about 2 percent of the total, the balance of the hydrocarbon emissions are divided between the petroleum industry and industrial and commercial uses of organic solvents.

Kinds of hydrocarbons contributed by these sources vary considerably. Auto exhaust, for example, is the principal source of olefins, though other sources connected with the operation of motor vehicles and with the processing and handling of gasoline contribute in direct proportion to the olefin content of the gasoline marketed here. All these sources contribute paraffins and aromatics, and emissions of hydrocarbons from solvent usage are composed almost entirely of these two classes.

Hydrocarbon derivatives

Of the 300 tons of hydrocarbon derivatives (or substituted hydrocarbons) emitted to the atmosphere of Los Angeles County each day, about three-fourths results from solvent uses such as surface coating, degreasing, and dry cleaning, and other industrial and commercial processes. The balance is included in the products of combustion of various petroleum fuels and of incineration of refuse. The substituted hydrocarbons emitted to the atmosphere by industrial and commercial use of organic solvents include oxygenates, such as aldehydes, ketones, and alcohols; organic acids; and chlorinated hydrocarbons. Most hydrocarbon derivatives associated with surface coating are oxygenates whose presence can be related either to the solvent itself or to the products of the partial oxidation involved in the drying of the coated objects. The hydrocarbon derivatives associated with degreasing and dry cleaning are mostly chlorinated hydrocarbons. The derivatives associated with combustion, either

Table 1. AIR CONTAMINANTS IN LOS ANGELES COUNTY, THEIR PRINCIPAL SOURCES AND SIGNIFICANCE (JANUARY 1964)

Emitted contaminant	Principal sources	Significant effects					
		Plant damage	Eye irritation	Oxidant formation	Visibility reduction	Danger to health	Other
Organic gases							
Hydrocarbons							
Paraffins	Processing and transfer of petroleum products; use of solvents; motor vehicles		X	X	X		
Olefins	Processing and transfer of gasoline; motor vehicles	X	X	X	X		
Aromatics	Same as for paraffins	X (Atypical)	X	X	X		Odors
Others							
Oxygenated hydrocarbons (Aldehydes, ketones, alcohols, acids)	Use of solvents; motor vehicles		X	X	X		
Halogenated hydrocarbons (Carbon tetrachloride, perchloroethylene, etc)	Use of solvents		X	X	X		Odors
Inorganic gases							
Oxides of nitrogen (Nitric oxide, nitrogen dioxide)	Combustion of fuels; motor vehicles	X	X	X	X	X	
Oxides of sulfur (Sulfur dioxide, sulfur trioxide)	Combustion of fuels; chemical industry	X (Specific type)	X		X	X	
Carbon monoxide	Motor vehicles; petroleum refining; metals industry; piston-driven aircraft					X (Occasionally)	
Aerosols							
Solid particles							
Carbon or soot particles	Combustion of fuels; motor vehicles				X	X (Under special circumstances)	
Metal oxides and salts	Catalyst dusts from refineries; motor vehicle exhaust; combustion of fuel oil; metals industry				X		
Silicates and mineral dusts	Minerals industry; construction				X		
Metallic fumes	Metals industry				X		
Liquid particles							
Acid droplets	Combustion of fuels; plating; battery manufacture				X		
Oily or tarry droplets	Motor vehicles; asphalt paving and roofing; asphalt saturators; petroleum refining				X		
Paints and surface coatings	Various industries						Property damage

of fuels or of refuse, are products of incomplete combustion and are almost entirely oxygenates. Thus, the composition of atmospheric emissions of hydrocarbon derivatives is currently about one-fourth to one-third chlorinated hydrocarbons and two-thirds to three-fourths oxygenates.

In addition to the hydrocarbon derivatives contributed by direct emissions, the atmosphere of a photochemical smog contains similar compounds formed there as a result of the reactions that produced the smog. These substituted hydrocarbons include oxygenates, such as aldehydes, ketones, alcohols, and organic acids, and nitrogen-containing compounds, such as the peroxyacyl nitrates and, perhaps, nitro olefins. These compounds are the products of partial oxidation of hydrocarbons and some derivatives in the atmosphere and of atmospheric reactions between oxides of nitrogen and organic gases.

Significance in Air Pollution Problem

Hydrocarbons and their derivatives are important factors in the air pollution problem in Los Angeles County because of their ability to participate in the atmospheric reactions that produce effects associated with photochemical smog. The most reactive group, the olefins (unsaturated hydrocarbons), can react with nitrogen dioxide to produce plant damage, eye irritation, visibility-reducing aerosols, and oxidants or ozone. Paraffins (saturated hydrocarbons) can also react with nitrogen dioxide to produce all these effects except plant damage. Aromatic hydrocarbons, particularly those having various substituent groups, can react with nitrogen dioxide to produce a type of plant damage different from that usually associated with smog and produce all the other effects as well.

The hydrocarbon derivatives, particularly the aldehydes and ketones, and even some of the chlorinated hydrocarbons, can also react with nitrogen dioxide in the atmosphere to produce eye irritation, aerosols, and ozone. Further, some of the aldehydes and nitro derivatives are, themselves, lachrymators and some of the chlorinated hydrocarbons are rather toxic. Except for the peroxyacyl nitrates, these compounds are not, however, generally associated with production of plant damage.

The hydrocarbons are further indicted because photochemical reactions in which they participate sometimes produce hydrocarbon derivatives such as aldehydes, ketones, and nitro-substituted organics, which can in turn react to increase the production of smog effects.

INORGANIC GASES

Inorganic gases constitute the second major group of air contaminants in Los Angeles County. They include oxides of nitrogen, oxides of sulfur, carbon monoxide, and much smaller quantities of ammonia, hydrogen sulfide, and chlorine.

The principal source of all the oxides listed above is the combustion of fuel for industrial, commercial, and domestic uses; for transportation; for space heating; and for generation of power. Additionally, small quantities of sulfur oxides and carbon monoxide, and the total of the minor constituents, ammonia, hydrogen sulfide, and chlorine, are emitted in connection with certain industrial processes.

Current Sources in Los Angeles County

The principal sources currently responsible for atmospheric emissions of each of the important inorganic gaseous air contaminants will now be discussed.

Oxides of nitrogen

A number of compounds must be classified as oxides of nitrogen, but only two, nitric oxide (NO) and nitrogen dioxide (NO_2), are important as air contaminants. The first, nitric oxide, is formed through the direct combination of nitrogen and oxygen from the air in the intense heat of any combustion process. Nitric oxide in the atmosphere is then able, in the presence of sunlight, to combine with additional oxygen to form nitrogen dioxide.

Usually the concentrations of nitric oxide in the combustion effluents are at least 5 to 10 times greater than those of nitrogen dioxide. Nonetheless, since every mole of nitric oxide emitted to the atmosphere has the potential to produce a mole of nitrogen dioxide, one may not be considered without the other. In fact, measurement of their concentrations often provides only a sum of the two reported as the dioxide.

Of the total quantities of these contaminants currently being emitted each day in Los Angeles County, approximately 60 percent, or 490 tons, must be attributed to the exhaust effluents from gasoline-powered motor vehicles. Almost the entire balance is produced as the result of combustion of fuel for space heating and power generation.

Oxides of sulfur

Air contaminants classified as oxides of sulfur consist essentially of only two compounds, sulfur dioxide (SO_2) and sulfur trioxide (SO_3). The primary source of both is the combination of atmospheric oxygen with the sulfur in certain fuels during their combustion. The total emitted quantities of these substances are, therefore, directly related to the sulfur content and total quantities of

the principal fuels used in a community. Normally, the dioxide is emitted in much greater quantities than the trioxide, the latter being formed only under rather unusual conditions. In fact, the trioxide is normally a finely divided aerosol rather than a gas.

In Los Angeles County during the past few years, the average daily emissions of sulfur oxides have exhibited a marked seasonal variation as a result of the promulgation of Rule 62. This rule places a limitation on the sulfur content of the fuels that may be burned during the period April 15 to November 15. The effect of this rule is to cause substitution of natural gas for fuel oil as the fuel used for generation of electric power. Since natural gas contains no sulfur, the emissions of sulfur oxides are thus drastically reduced during this period. Recent appraisals of total air pollution for Los Angeles County must take this fact into account.

During the period April 15 to November 15, therefore, emissions of sulfur oxides total approximately 60 tons per day, 10 percent of which is attributable to combustion of fuels for power generation and space heating; 50 percent, to emissions from sulfur and sulfuric acid plants; and the remainder about evenly divided between emissions from petroleum-refining operations and emissions from automobile exhausts. During the balance of the year, however, nearly 80 percent of the total of 455 tons of emissions of sulfur oxides per day must be attributed to combustion of fuel for power generation and space heating; 10 percent, to emissions from industrial sulfur recovery operations; and the balance about evenly divided between emissions from petroleum-refining operations and automobile exhausts.

Seasonal variations in emissions of sulfur oxides are less likely to occur in the future because of Rule 62.1, adopted in 1964. This rule prohibits the burning of fuels of high sulfur content at any time when natural gas or low-sulfur fuels are available. In the near future, however, natural gas may not always be available during the winter months.

Carbon monoxide

Carbon monoxide (CO) is a single contaminant formed during incomplete oxidation of any carbonaceous fuel and currently has only one significant source in Los Angeles County--the incomplete combustion of gasoline in motor vehicles. Of a total of nearly 10,660 tons of this contaminant emitted per day, 97 percent is attributable to this source. About 1.5 percent is attributable to the emissions from aircraft, and the balance, from petroleum-refining operations.

Significance in Air Pollution Problem

The importance of the inorganic gases in an air pollution problem varies with the gas in question. Each will, therefore, be discussed separately.

Oxides of nitrogen

The oxides of nitrogen have far greater significance in photochemical smog than any of the other inorganic gaseous contaminants. Research has demonstrated that nitrogen dioxide in the presence of sunlight will undergo reactions with a number of organic compounds to produce all the effects associated with photochemical smog. In fact, the presence of the dioxide has been shown to be a necessary condition for these reactions. This does not, however, diminish the need for adequate consideration of nitric oxide as an air contaminant, since this is the form in which the oxides of nitrogen normally enter the atmosphere. If it were possible to prevent the oxidation of nitric oxide to nitrogen dioxide, there would, perhaps, be little reason to consider the oxides of nitrogen as air contaminants, at least in Los Angeles.

In communities not affected by photochemical smog, the oxides of nitrogen must be considered solely for their inherent ability to produce deleterious effects by themselves. The only effect that must seriously be considered in this regard is their toxicity, though the reddish-brown color of the dioxide and its sharp odor could cause problems in areas near a nylon plant, nitric acid plant, or nitrate fertilizer plant. Nitric oxide is considerably less toxic than the dioxide. It acts as an asphyxiant when in concentrations great enough to reduce the normal oxygen supply from the air. Nitrogen dioxide, on the other hand, in concentrations of approximately 5 ppm, can produce lung injury and edema, and in greater concentrations, fatal lung damage.

The dioxide, then, is heavily indicted as an undesirable constituent of the atmosphere, regardless of the type of air pollution problem under consideration. Nitric oxide is indicted, too, because of its ability to produce the dioxide by atmospheric oxidation.

Fortunately, no link between atmospheric concentrations of nitrogen oxides and actual injury or illness in humans or animals has been reported yet. Hopefully, recognition of the potential danger will prevent any incident.

Oxides of sulfur

During the past few years, information in the literature has indicated that the presence of sulfur

dioxide in the photochemical-smog reaction enhances the formation of visibility-reducing aerosols. The mechanism responsible for this effect has not been described, and it is not known whether sulfur dioxide enters into the organic photochemical reactions or whether the additional aerosols observed represent simply a combination of sulfur dioxide and moisture.

Primarily, gaseous oxides of sulfur in the atmosphere are significant because of their toxicity. Both the dioxide and trioxide are capable of producing illness and lung injury even at small concentrations, from 5 to 10 ppm. Further, each can combine with water in the air to form toxic acid aerosols that can corrode metal surfaces, fabrics, and the leaves of plants. Sulfur dioxide by itself also produces a characteristic type of damage to vegetation whereby portions of the plants' leaves are bleached in a specific pattern. In concentrations as small as 5 ppm, sulfur dioxide is irritating to the eyes and respiratory system.

Both the dioxide and trioxide can combine with particles of soot and other aerosols to produce contaminants more toxic than either alone. The combination of the dioxide and trioxide with their acid aerosols has also been found to exert a synergistic effect on their individual toxicities. These mixtures were apparently responsible for the illness and death associated with the famous air pollution incidents that occurred in the Meuse Valley, Belgium; in Donora, Pennsylvania; and, more recently, in London, England.

Carbon monoxide

Carbon monoxide plays no part in the formation of photochemical smog though it is almost invariably emitted to the atmosphere along with the most potent of smog formers--hydrocarbons and oxides of nitrogen. At concentrations of 200 ppm and greater, it produces illness and death by depriving the blood of its oxygen-carrying capacity. It has been detected in the atmosphere of various urban centers of the world at concentrations from 10 to 100 ppm. Greater concentrations have occasionally been measured in confined spaces such as tunnels and large, poorly ventilated garages. Atmospheric concentrations have not yet been linked to fatalities but have sometimes been implicated in short-term illnesses of traffic officers.

Miscellaneous inorganic gases

A few additional gases were listed among those emitted to the atmosphere from various operations in Los Angeles County. They include ammonia, hydrogen sulfide, chlorine, and fluorine or fluorides. Although none has been detected in greater than trace quantities in the Los Angeles atmosphere and none is known to have any significance in the formation of photochemical smog, these contaminants can be important in other types of air pollution problems. All are toxic in small to moderate concentrations, and the first three have unpleasant odors. Hydrogen sulfide can cause discoloration of certain kinds of paint; ammonia and chlorine can discolor certain fabric dyes; fluorine and fluorides, especially hydrogen fluoride, are highly toxic, corrosive, and capable of causing damage to vegetation, and illness and injury to humans and animals.

Many other inorganic gases may be individually or locally objectionable or toxic. These are of relatively minor importance and will not be discussed here.

AEROSOLS

Aerosols (also called particulate matter) present in the atmosphere may be organic or inorganic in composition, and in liquid or solid physical state. By definition, they must be particles of very small size or they will not remain dispersed in the atmosphere. Among the most common are carbon or soot particles; metallic oxides and salts; oily or tarry droplets; acid droplets; silicates and other inorganic dusts; and metallic fumes.

The quantities of aerosols emitted in Los Angeles County, at present, are relatively small but include at least some amounts of all the types listed above. Particles of larger than aerosol size are also emitted but, because of their weight, do not long remain airborne. Additionally, however, vast quantities of aerosols are formed in the atmosphere as the result of photochemical reactions among emitted contaminants. Total quantities of these aerosols may easily exceed those of emitted aerosols, at least in terms of particle numbers.

Current Sources in Los Angeles County

The most important current sources of aerosol emissions in Los Angeles County, by type of aerosol, will now be discussed.

Carbon or soot particles

Probably the most commonly emitted kind of particle anywhere is carbon. Carbon particles are nearly always present among the products of combustion from all types of fuels, even from operations in which the combustion is apparently complete.

In Los Angeles County, the principal sources of emissions containing carbon or soot particles are the exhaust effluents from motor vehicles, and the combustion of fuels for power generation and

space heating, though not all the particulates emitted from these sources are carbon. Emissions from the latter group of sources vary with the Rule 62 period* since these particles occur in greater quantities in the effluent from the burning of fuel oil than in that from the burning of natural gas. During Rule 62 periods, then, the combustion of fuel for space heating and generation of power accounts for about one-fourth of the carbon particles emitted to the atmosphere, and during non-Rule 62 periods, about one-half. The portion contributed by auto exhaust varies, therefore, during comparable periods from one-half to three-fourths of the total.

The actual total of emitted carbon particles cannot be estimated with much accuracy, but they probably represent about one-third to one-half of the total aerosol emissions.

The only other sources from which significant quantities of carbon particles might be emitted are incineration of refuse, operation of piston-driven aircraft, and operation of ships and railroads. Even the total of particulate emissions from these sources does not, however, comprise 5 percent of the total of carbon emissions.

Metallic oxides and salts

Metallic oxides and salts can be found in small quantities in the emissions from many sources. These sources include catalyst dusts from refinery operations, emissions from the metals industry, effluents from combustion of fuel oil, and even exhaust from motor vehicles. The total quantity of these emissions is, however, small and probably does not constitute more than 5 to 10 percent of the total particulate emitted to the atmosphere.

The materials emitted as catalyst dusts are mostly oxides. Small quantities of metallic oxides may also result from the combustion of fuel oil and perhaps from metal-working operations. These oxides might include those of vanadium, aluminum, titanium, molybdenum, calcium, iron, barium, lead, manganese, zinc, copper, nickel, magnesium, chromium, and silver.

Metallic salts are emitted from essentially the same sources--again, in small concentrations. Most emissions of particulate lead in auto exhaust, for example, are present as oxides and complex salts, usually chlorides, bromides, and sulfates. Metallic oxides are emitted from certain metals operations, and small quantities of sulfates are emitted from some industrial operations.

*April 15 to November 15.

Oily or tarry droplets

Small droplets of oily or tarry materials are frequently found in combustion effluents from many types of sources. The most common sources are probably the emissions associated with the operation of motor vehicles, particularly crankcase emissions; exhaust emissions from gasoline- and diesel-powered vehicles; effluents from asphalt manufacturing, saturating, paving, and roofing operations; and effluents from inefficient combustion of fuels in stationary sources. Small amounts might also be found in the effluents from aircraft, ships, and locomotives and from incineration of refuse. Oily or tarry particles also appear to be among the products of the photochemical reactions that produce smog. Emitted quantities of these materials probably comprise 10 to 20 percent of the total particulate emissions.

Although the composition of these materials is not well established, they appear to be predominantly organic. They undoubtedly have relatively high molecular weights and probably contain at least some aromatics. The polycyclic hydrocarbons, which currently cause so much concern, probably occur in a liquid phase in the atmosphere.

Acid droplets

Small droplets of acid, both organic and inorganic, are emitted from a number of sources in Los Angeles County under certain conditions. These sources include stack effluents from power plants, especially during combustion of fuel oil; effluents from industrial operations such as certain metal-working and plating operations, and storage battery reclamation; effluents from waste rendering and incineration; and even effluents from motor vehicle exhaust. Under some circumstances, these acid droplets are also formed in the atmosphere. Like the other kinds of particulate matter, the total emitted quantities of these droplets are small, probably 5 to 10 percent of the total particulate emissions. Even the quantities of these materials formed in the atmosphere are small relative to the total.

The inorganic acids emitted to the atmosphere include, primarily, sulfuric and nitric acids; the organic acids include probably acetic, propionic, and butyric acids. The acids formed in the atmosphere through combination of gases with water include sulfurous, sulfuric, nitrous, and nitric acids. Acid droplets formed through oxidation of organic emissions may not include any but acetic acid, if that.

Silicates and other inorganic dusts

Emissions of inorganic dusts in Los Angeles County consist primarily of silicates, carbonates, and oxides and are probably associated most commonly with quarrying operations, sand and gravel plants, and other phases of the minerals industry. They can also result from highway construction and landfill operations. Their quantity may represent about 5 to 10 percent of the total particulate emissions.

Metallic fumes

The metals industry is probably responsible for 5 to 10 percent of the total aerosol emissions, and metal fumes probably constitute less than half of this portion. Metal fumes are generally considered to be minute particles created by the condensation of metals that have vaporized or sublimed from the molten state.

Significance in Air Pollution Problem

The significance of aerosols, and of all airborne particulate matter, varies with the type of air pollution problem in which they are involved. In most situations, particulate emissions represent a major portion of the total quantity of air contaminants and would be important for their soiling and and nuisance properties alone, if for no other. Even in air pollution problems of the type produced by coal burning, which involves only carbon particles, ash, and oxides of sulfur, there are indications that the toxic effect of the sulfur dioxide and trioxide is enhanced by the concomitant particulate matter. This kind of effect has been noted in other cases involving aerosols and toxic gases or liquids and has given rise to the theory that other contaminants can adsorb on the surface of the particles and thus come into contact with inner surfaces of the lungs and mucous membranes in much greater concentrations than would otherwise be possible.

Particulate emissions are also associated with reduction of visibility. In some instances, this is the simple physical phenomenon of obscuration of visibility by the quantity of interfering material. In those instances associated with photochemical smog, however, the visibility reduction is due to refraction and scattering of light, and the number and size of the particles involved are much more important than their identities. The smaller the particles (maximum reduction of visibility at 0.7 micron) and the larger their number, the greater their collective effect on visibility.

It has also been suggested that the presence of minute particles promotes the photochemical reactions that produce smog. Furthermore, small aerosol particles are among the products of these reactions and add to the visibility reduction produced by the emitted contaminants.

AIR POLLUTION CONTROLS ALREADY IN EFFECT

When the air pollution problem in Los Angeles County was recognized, an agency was immediately provided to study the problem and try to solve it. The first Air Pollution Control District in California was formed and charged with responsibility for the elimination or, at least, significant reduction of air pollution in Los Angeles County.

During its first 10 years, the District concentrated its efforts on control of emissions from stationary sources. Experience of other agencies in this field had shown that certain kinds of industrial emissions were most commonly responsible for air pollution problems. Mobile equipment was exempted from control and not at that time considered a serious source of contaminants.

Continuous study and diligence have since led to the promulgation of the most stringent and complete rules and regulations in force anywhere in the world and to the most effective control program currently feasible. Both are frequently copied and studied. Table 2 concisely summarizes what has been accomplished. Other sections of this manual explain in detail the methods and equipment used.

Perhaps the most graphic evidence of the success of this control effort is the almost complete absence of emissions from stacks and chimneys anywhere in the Los Angeles Basin. Any source of visible emissions immediately calls attention to itself.

CONTROL MEASURES STILL NEEDED

Despite an almost incredibly successful program of control over stationary-source emissions, the persistence of unpleasant effects of air pollution and the concentrations of atmospheric contaminants still being measured did not properly reflect these dramatic reductions. A research program undertaken concurrently with the programs of control and enforcement had revealed that the air pollution problem in the Los Angeles area was different from that usually encountered. It had shown also that the hydrocarbons and oxides of nitrogen primarily responsible for the effects associated with smog in Los Angeles were likely to be emitted only in connection with the processing and handling of petroleum and the combustion of fuels.

As soon as hydrocarbons were recognized to be of great significance in this kind of air pollution problem, measures were undertaken to control the

Table 2. EFFECT OF LOS ANGELES COUNTY AIR POLLUTION CONTROL DISTRICT'S RULES ON EMISSIONS FROM STATIONARY SOURCES (JANUARY 1965)

| Emission source category | Contaminants prevented from entering the Los Angeles County atmosphere, tons per day[b] | | |

emissions from their principal stationary sources, the refineries. Although these measures failed to eliminate smog effects throughout the basin, they diminished these effects and reduced the atmospheric hydrocarbon concentrations in the refinery area of the county. At the same time, however, damage to plants, irritation of eyes, and reduction in visibility were more widespread and increasing in severity in suburban areas that had previously been almost smog free. Obviously, some important source of the contaminants that produce photochemical smog had not been adequately taken into account. This source proved to be the most prevalent consumer of petroleum products, the gasoline-powered motor vehicle.

Although no feasible means for control of motor vehicle emissions were yet known and mobile sources were then exempt from control, assessment of the relative importance of this source of emissions was clearly mandatory. Investigation of exhaust emissions revealed that, although each individual vehicle was negligible as a source, the vast number of vehicles could have great significance. Further study demonstrated how the phenomenal postwar growth of the Los Angeles area had so increased the sources of air contaminants that the gains made by the control of stationary sources had been almost nullified. From 1945 to 1955, for example, the pollution of Los Angeles County increased by almost 50 percent; motor vehicle registration and gasoline consumption increased about 100 percent; and the number of industrial establishments increased by nearly 80 percent. The district had had to "run at great speed to stay in one place," and the picture of what the situation might have been without a control program was almost unimaginable.

Estimating the total quantities of air pollution in Los Angeles County, the district was able to determine that hydrocarbon emissions from motor vehicles as a fraction of the total for the county had probably increased from about one-eighth in 1940 to one-third in 1950 and to one-half to two-thirds in 1955. Oxides of nitrogen emissions from motor vehicles probably constituted about 50 percent of the total in 1940 and 1950, and 50 to 60 percent in 1955. During the entire period, motor vehicle emissions probably accounted for 85 to 95 percent of the total of carbon monoxide emitted to the atmosphere. These estimates represent the net effect of both growth and control measures and illustrate the change in emphasis that has gradually taken place. Probably this would, however, be less true of areas that had little or no control over emissions from stationary sources.

MOTOR VEHICLE EMISSIONS

For Los Angeles County, this gradual change and its effect on the solution of the air pollution problem had to be carefully evaluated, and the probable necessity for control of motor vehicle emissions, prudently considered. In 1957, though no controls were available, appropriate steps were taken to enable the district to encourage the development of necessary control devices and require their use when they became available. Additional study, plus the increasing occurrence of the effects of photochemical smog in other areas of California, suggested that control of mobile sources at the local, or district, level probably would not be adequate. In 1959, therefore, the state government formally occupied this particular field of air pollution control in California. Although the Los Angeles County Air Pollution Control District continued its participation in research on vehicular emissions, its primary responsibility reverted to control of emissions from stationary sources.

ADDITIONAL CONTROLS OVER STATIONARY SOURCES

The principal areas in which additional controls will be needed involve reduction of emissions of organic gases and oxides of nitrogen. Present control measures have so far brought about only 61 and 45 percent control, respectively, of these emissions from stationary sources. Obviously, control of these emissions from motor vehicles is also necessary, but this is no longer the district's responsibility.

Organic Gases

Judged from percent of control already achieved, additional control of emissions of organic gases could apparently be accomplished in four areas: combustion of fuels, marketing of petroleum, manufacture of chemicals, and use of organic solvents. Only two, use of organic solvents and marketing of petroleum, present much opportunity for significant reductions. Both have been studied by the district to determine what control methods are available and how much additional control could be achieved. Possible control methods for organic solvent emissions include: substitution of water-base paints and coatings; solvent absorption or adsorption and recovery; and incineration of combustible emissions. Possible methods for control of hydrocarbons emitted during marketing of petroleum products include: absorption (or condensation) and recovery, and use of vapor return equipment during transfer operations. The feasibility and economics of each will be discussed in more detail in other sections of this manual.

Control of these two sources during earlier programs of the district was not considered necessary. With continued growth of the area and reduction of emissions from other sources, however, the relative and absolute magnitudes of these emissions have increased to the point where control

must be undertaken. Increased emissions from petroleum marketing have simply come with increased use of gasoline. Increased emissions from solvent use reflect the increase in usage related to the growth of the area and the technological advances illustrated by the growing demand for dry cleaning solvents, especially since the advent of coin-operated machines.

Oxides of Nitrogen

Additional reduction of oxides of nitrogen emissions from stationary sources poses a diffifult problem. Significant quantities are emitted only in connection with combustion of fuels. The reduction that has already been achieved was accomplished through substitution of natural gas for fuel oil during 7 months of the year. Rule 62.1, which was adopted in 1964, will bring about additional reduction, but even combustion of natural gas produces some oxides of nitrogen, and there is a point beyond which control cannot be extended by this means. Research into the nature of combustion has suggested that control of formation of oxides of nitrogen may be possible through changes in design of combustion equipment and through rigorous control of combustion conditions.

Oxides of Sulfur

Rule 62.1 will also bring about additional reduction in emissions of the oxides of sulfur. Further control over emissions of these contaminants would also appear to be possible in the chemical industry. This is not, however, necessarily true, since most of these emissions come from sulfur recovery operations that represent excellent and profitable elimination of sulfur oxides emissions from refineries. Additional control in this area is not feasible at this time.

Other Contaminants

There are no other areas in which significant additional reduction of contaminant emissions can be accomplished at present. Continued surveillance of all contaminant emissions will, of course, be maintained. If any emissions are found to have increased to the point where more stringent control is necessary or if means are discovered to make certain additional controls feasible, the proper steps to put these into effect will be taken immediately.

CHAPTER 3

DESIGN OF LOCAL EXHAUST SYSTEMS

FLUID FLOW FUNDAMENTALS

HERBERT SIMON, Senior Air Pollution Engineer

JOHN L. McGINNITY, Intermediate Air Pollution Engineer*

JOHN L. SPINKS, Air Pollution Engineer

HOOD DESIGN

HERBERT SIMON, Senior Air Pollution Engineer

DUCT DESIGN

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

FAN DESIGN

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

LEWIS K. SMITH, Air Pollution Engineer

VAPOR COMPRESSORS

GEORGE THOMAS, Intermediate Air Pollution Engineer

CHECKING AN EXHAUST SYSTEM

JOSEPH D'IMPERIO, Air Pollution Engineer†

COOLING OF GASEOUS EFFLUENTS

GEORGE THOMAS, Intermediate Air Pollution Engineer

*Now with the National Center for Air Pollution Control, Public Health Service, U.S. Department of Health, Education, and Welfare.

†Now deceased.

CHAPTER 3

DESIGN OF LOCAL EXHAUST SYSTEMS

FLUID FLOW FUNDAMENTALS

Local exhaust systems are devices used to capture dusts and fumes or other contaminants at their source and prevent the discharge of these contaminants into the atmosphere. Close-fitting hoods are used to capture the contaminants from one or more locations so that the laden gases can by conveyed through a system of ducts by one or more exhaust fans. An air pollution control device can then be used to collect the air contaminants and discharge the cleansed air into the atmosphere.

In designing a local exhaust system, sufficient air must be provided for essentially complete pickup of the contaminants. Conversely, too much air can result in excessive construction and operation costs. It is, therefore, necessary for the designer to understand certain physical principles that are useful in analyzing the ventilation needs and in selecting the hooding devices.

The nature of flow of a real fluid is very complex. The basic laws describing the complete motion of a fluid are, in general, unknown. Some simple cases of laminar flow, however, may be computed analytically. For turbulent flow, on the other hand, only a partial analysis can be made, by using the principles of mechanics. The flow in exhaust systems is always turbulent; therefore, the final solution to these problems depends upon experimental data.

BERNOULLI'S EQUATION

The basic energy equation of a frictionless, incompressible fluid for the case of steady flow along a single streamline is given by Bernoulli as

$$h + \frac{p}{\gamma} + \frac{v^2}{2g} = C \qquad (1)$$

where

h = elevation above any arbitrary datum, ft

p = pressure, lb/ft^2

γ = specific weight, lb/ft^2

v = velocity, ft/sec

g = acceleration due to gravity, 32.17 ft/sec^2

C = a constant, different for each streamline.

Each term in Bernoulli's equation has the units foot-pounds per pound of fluid or feet of fluid. These terms are frequently referred to as elevation head, pressure head, and velocity head. They also represent the potential energy, pressure energy, and velocity energy, respectively.

When Bernoulli's equation is applied to industrial exhaust systems, the elevation term is usually omitted, since only relatively small changes in elevation are involved. Since all streamlines originate from a reservoir of constant energy (the atmosphere), the constant is the same for all streamlines, and the restriction of the equation to a single streamline can be removed. Furthermore, since the pressure changes in nearly all exhaust systems are at most only a few percent of the absolute pressure, the assumption of incompressibility may be made with negligible error. Although steady-flow conditions do not always exist in exhaust systems, it is safe to make the assumption of steady flow if the worst possible case is considered. Any error will then be on the safe side.

All real fluids have a property called viscosity. Viscosity accounts for energy losses, which are the result of shear stresses during flow. The magnitude of the losses must be determined experimentally, but once established, the values can be applied to dynamically similar configurations. Bernoulli's equation may be applied to a real fluid by adding an energy loss term. Letting 1 be an upstream point and 2 a downstream point, the energy per unit weight at 1 is equal to the energy per unit weight at 2 plus all energy losses between point 1 and point 2.

PITOT TUBE FOR FLOW MEASUREMENT

The velocity of a fluid (liquid) flowing in an open channel may be measured by means of a simple pitot tube, as shown in Figure 2 (Streeter, 1951). Although this instrument is simple, usually consisting of a glass tube with a right-angle bend, it is one of the most accurate means of measuring velocity. When the tube opening is directed upstream, the fluid flows into the tube until the pressure intensity builds up within the tube sufficiently to withstand the impact of velocity against it. The fluid at a point directly in front of the tube (stagnation point) is then at rest. The pressure at the stagnation point is known from the height of the liquid column in the tube. The velocity of the fluid

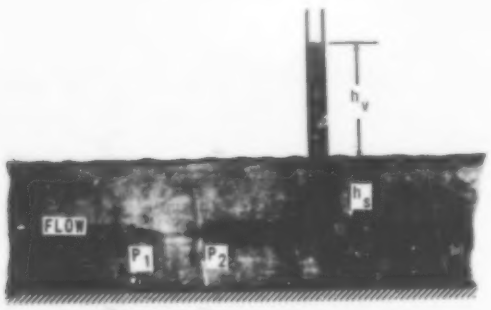


Figure 2. Simple pitot tube (Streeter, 1951).

in the stream may be evaluated by writing Bernoulli's equation between point 1 upstream of the stagnation point and point 2 the stagnation point. Note that $h_1 = h_2$ and $v_2 = 0$. Therefore

$$\frac{v_1^2}{2g} + \frac{P_1}{\gamma} = \frac{P_2}{\gamma} = \frac{P_1}{\gamma} + \Delta h \qquad (2)$$

solving for the velocity,

$$v_1 = \sqrt{2g\,\Delta h} \qquad (3)$$

A simple pitot tube measures the total head or total pressure, which is composed of two parts, as shown in Figure 2. These are the static pressure h_s and the dynamic or velocity pressure h_v. In open-channel flow, h_v is measured from the free surface. When the fluid is in a pipe or conduit in which it flows full, a simple pitot tube will again indicate the total pressure, but now the portion of the total head caused by velocity cannot be distinguished. The static pressure in this case can be measured by a piezometer or static tube, as shown in Figure 3. The total pressure H consists of the sum of the static pressure h_s and the velocity pressure h_v, or

$$H = h_s + h_v \qquad (4)$$

The velocity can be determined, therefore, from the difference between the total and static heads.

In practice, measurement of total pressure and static pressure is combined into a single instrument (pitot-static tube, Figure 4), which permits direct measurement of velocity head since the static head is automatically subtracted from the total head. An inclined manometer (Ellison gauge) is particularly useful when the heads are small as in exhaust systems. Use of this device to measure the flow of a gas introduces, however, an additional factor, which is the conversion of readings in inches of manometer fluid into meaningful velocity terms. This relationship, when water is used as the manometer fluid to measure the velocity of air, is

$$h_v = \left(\frac{v_a}{4005}\right)^2 \qquad (5)$$

where

h_v = velocity pressure or head, inches of water

4005 = $1096.2\sqrt{\text{Volume in ft}^3 \text{ of 1 lb of air at 70°F and 14.7 psia}}$

v_a = velocity of air, fpm.

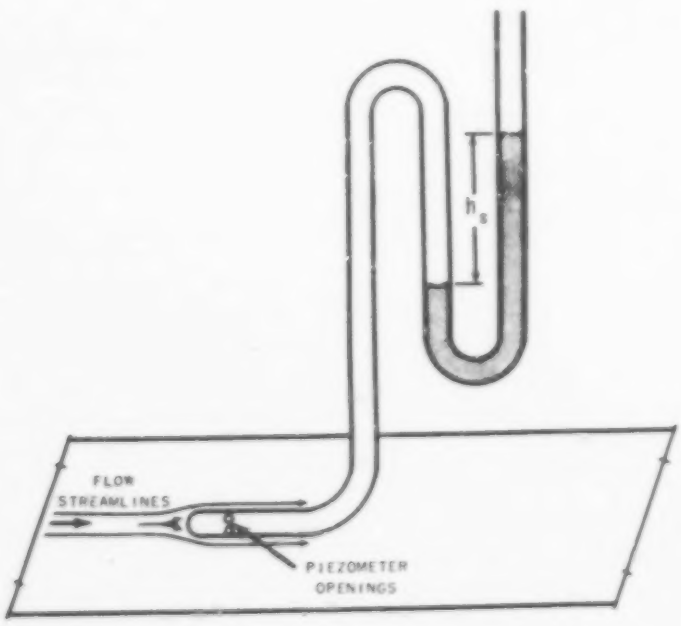


Figure 3. Static tube (Streeter, 1951).

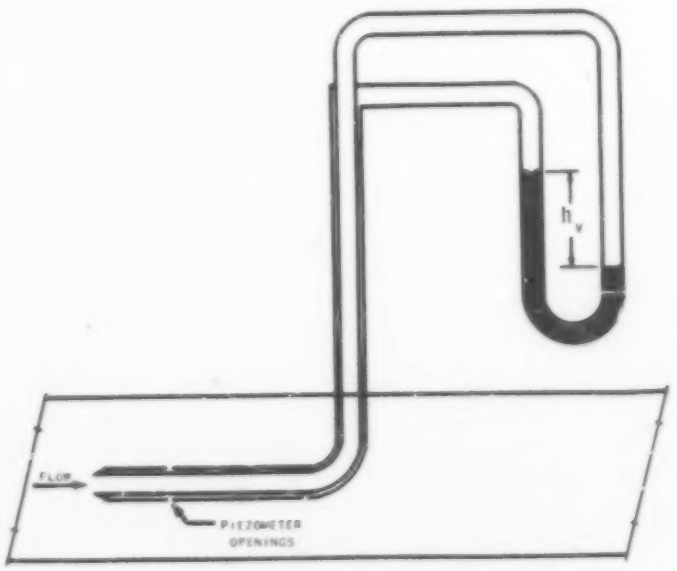


Figure 4. Pitot-static tube (Streeter, 1951).

Correction Factors

The relationship expressed in equation 5 is exact only for air at standard temperature and pressure, 70°F and 14.7 psia, respectively. A correction must be applied for other than standard conditions. If the air in the duct departs from 70°F by more than about 50°F, a correction is required:

$$h_v = \left(\frac{v_a}{4005}\right)^2 \left(\frac{460 + 70}{460 + t_a}\right) \qquad (6)$$

where

t_a = the temperature of the air, °F.

For smaller temperature deviations, the error is not significant and may be neglected. If the gas is other than air, a correction for the difference in density may be applied:

$$h_v = \left(\frac{v_a}{4005}\right)^2 \left(\frac{\text{density of gas}}{\text{density of air STP}}\right) \qquad (7)$$

where the density of the gas under conditions actually existing at the time of the measurement includes the effects of temperature, pressure, and molecular weight.

HOOD DESIGN

Hoods are devices used to ventilate process equipment by capturing emissions of heat or air contaminants, which are then conveyed through exhaust system ductwork to a more convenient discharge point or to air pollution control equipment. The quantity of air required to capture and convey the air contaminants depends upon the size and shape of the hood, its position relative to the points of emission, and the nature and quantity of the air contaminants.

Hoods can generally be classified into three broad groups: Enclosures, receiving hoods, and exterior hoods. Enclosures usually surround the point of emission, though sometimes one face may be partially or even completely open. Examples of this type are paint spray booths, abrasive blasting cabinets, totally enclosed bucket elevators, and enclosures for conveyor belt transfer points, mullers, vibrating screens, crushers, and so forth.

Receiving hoods are those wherein the air contaminants are injected into the hoods. For example, the hood for a grinder is designed to be in the path of the high-velocity dust particles. Inertial forces carry the air contaminants into the hood.

Exterior hoods must capture air contaminants that are being generated from a point outside the hood itself, sometimes some distance away. Exterior hoods are the most difficult to design, require the most air to control a given process, and are most sensitive to external conditions. For example, a hood that works well in a still atmosphere may be rendered completely ineffectual by even a slight draft through the area. The best rule to follow in hood design is to place the hood where the air contaminants are generated. Since this is not always physically possible, it is important to consider the design criteria for external hoods.

CONTINUITY EQUATION

The volume of air flow is dependent upon the cross-sectional area and the average velocity of the air. The relationship may be represented by the familiar equation

$$V_t = Av \qquad (8)$$

where

V_t = total air volume, cfm

A = cross-sectional area, ft^2

v = velocity, fpm.

The continuity equation (equation 8) shows that, for a given quantity of fluid, the velocity must increase if the area decreases. Imagine that air is being withdrawn from a point at the center of a large room. Since an imaginary point has no dimensions, there will be no interference with the flow of air toward the point. The air will, therefore, approach this point radially and at a uniform rate from all directions. The velocity of the air must increase as it passes through a succession of diminishing areas represented by spherical surfaces in its approach to the imaginary point, according to the relationship

$$v = \frac{V_t}{4\pi r^2} \qquad (9)$$

where

r = the distance from the imaginary point, ft.

AIR FLOW INTO A DUCT

If a circular duct opening, representing a simple hood, is substituted for the imaginary point, the pattern of flow into the end of the duct, or hood, will be modified as shown in Figure 5 because of the interference from the duct. The velocity of the air approaching a plain, circular opening along the axis of the duct is given by Dalla Valle (1952) as approximately

$$\frac{Y}{100 - Y} = \frac{0.1A}{x^2} \qquad (10)$$

where

Y = the percent of the velocity at the opening found at a point x on the axis

x = the distance outward along the axis from the opening, ft

A = the area of the opening, ft^2.

The velocity at the opening is computed from the continuity equation.

The actual flow pattern is found to be as shown in Figure 5 from studies by Dalla Valle and others. The lines of constant velocity are called contour lines, while those perpendicular to them are streamlines, which represent the direction of flow. The addition of a flange improves the efficiency of the duct as a hood for a distance of about one diameter from the duct face. Beyond this point, flanging the duct improves the efficiency only slightly. Figure 6 illustrates flow patterns for several sizes of square hoods. Because there is little difference in the center line velocity of hoods of equal air volume at a distance of one or two hood diameters from the hood face, Hemeon (1955) recommends using one equation for all shapes--square, circular, and rectangular up to about 3:1 length-to-width ratio. He also does not distinguish between flanged and unflanged hoods, which appears justified when these hoods are used only at distances of one diameter or more from the hood face. At close distances, flanged hoods are far superior at the same volume. By rearranging terms in equation 10 and combining with equation 8, the following is obtained:

$$V_t = v_x (10x^2 + A_f) \qquad (11)$$

where

V_t = the volume of air entering the hood, cfm

v_x = the velocity at point x, fpm

x = the distance to any point x on the axis or center line of the hood measured from the hood face, ft

A_f = the area of the hood face, ft^2.

Analysis of equation 11 shows that at the hood face x = 0 and the equation becomes identical to equation 8. For large values of x, the A_f term becomes less significant, as the evidence shows it should. To use equation 11, select a value of v_x that is sufficient to assure complete capture of the air contaminants at point x. From the physical dimensions and location of the hood, A_f and x are determined. The volume required may then be calculated.

While equation 11 applies to a freestanding or unobstructed hood, it can also be applied to a rectangular hood bounded on one side by a plane surface, as shown in Figure 7. The hood is considered to be twice its actual size, the additional portion being the mirror image of the actual hood and the bounding plane being the bisector. Equation 11 then becomes

$$V_t = v_x \left(\frac{10x^2 + 2A_f}{2} \right) \qquad (12)$$

where the terms have the same meaning as before.

NULL POINT

Air contaminants are often released into the atmosphere with considerable velocity at their point of generation. Because the mass is essentially small, however, the momentum is soon spent and the particles are then easily captured. Hemeon (1955) refers to a null point, shown in Figure 8, as the distance within which the initial energy of an emitted air contaminant has been dissipated or nullified in overcoming air resistance. If an adequate velocity toward the hood is provided at the farthest null point from the hood, all the air contaminants released from the process will be captured. What constitutes an adequate velocity towards the hood depends upon drafts in the area and cannot, therefore, be determined precisely.

Establishing the null point in advance for a new process is not always easy or even possible. For existing equipment, however, direct observation will usually establish a locus of null points. Obviously, in the absence of external disturbances, any positive velocity toward the hood at the farthest null point will give assurance of complete capture. When this is put into practice, however, the results are disappointing. Even closed rooms have drafts and thermal currents that destroy the hood's effectiveness unless a substantial velocity toward the hood is created at the farthest null point. Experience has shown that a velocity of less than 100 fpm at a null point can seldom, if ever, be tolerated without a loss in the hood's effectiveness.

Draft velocities in industrial situations may almost always be expected to be 200 to 300 fpm

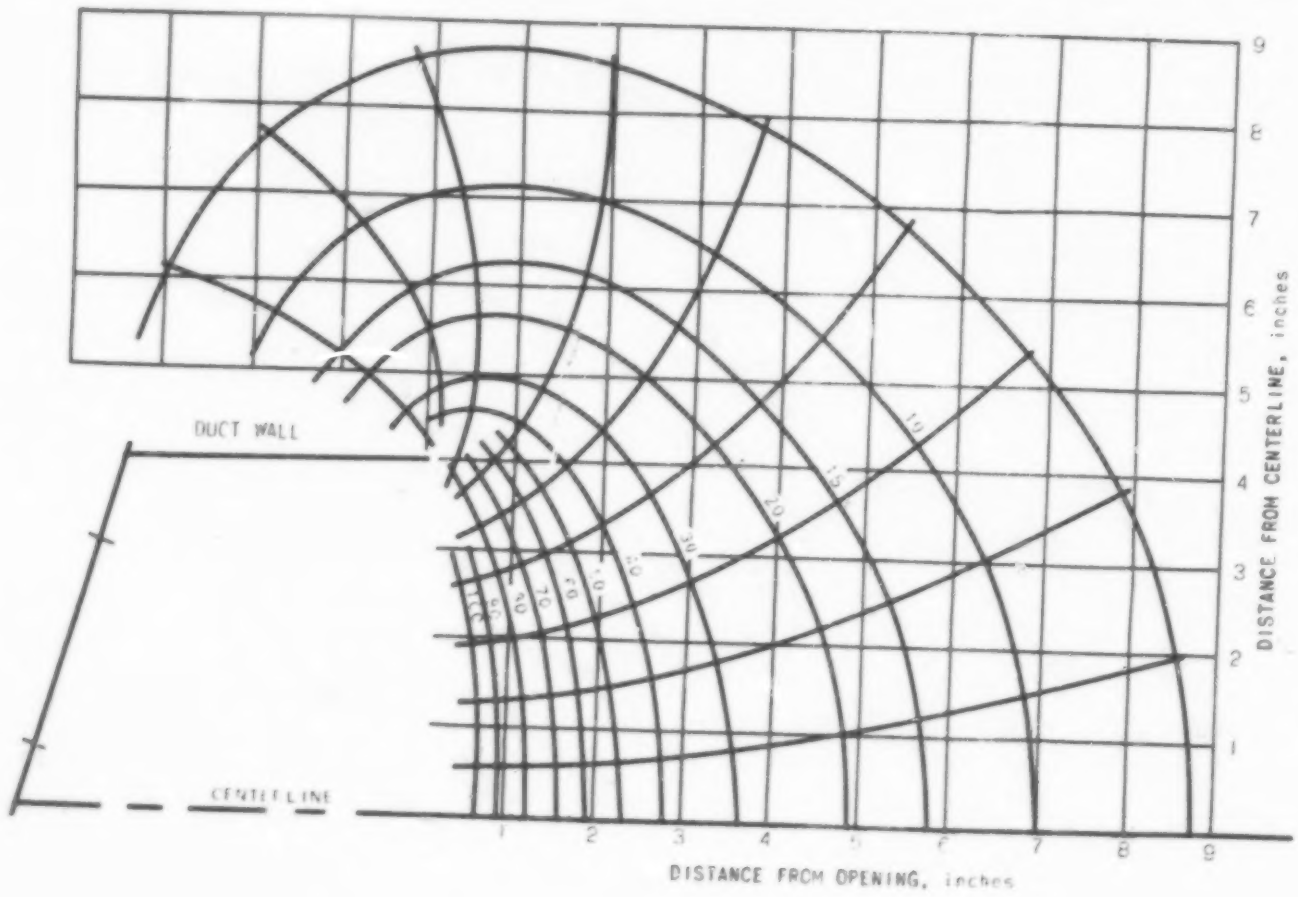


Figure 5. Actual flow contours and streamlines for flow into circular openings. Contours are expressed as percentage of opening velocity (Dalla Valle, 1952).

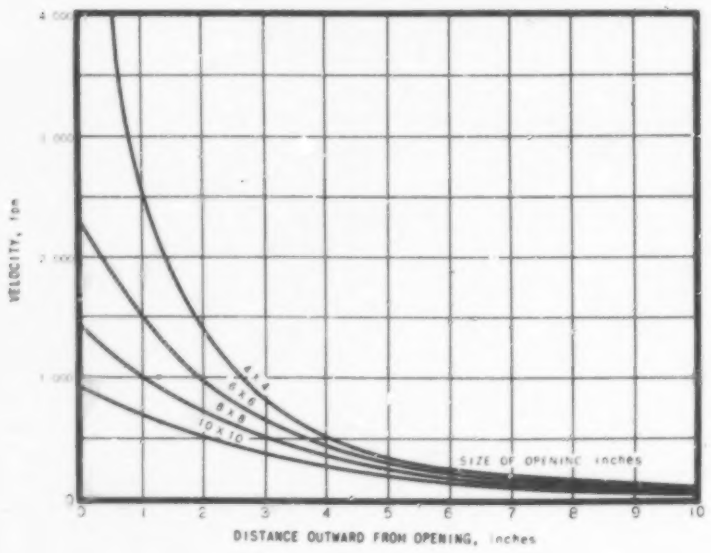


Figure 6. Actual velocities for square openings of different sizes. Air flow through each opening is 500 cfm (Dalla Valle, 1952).

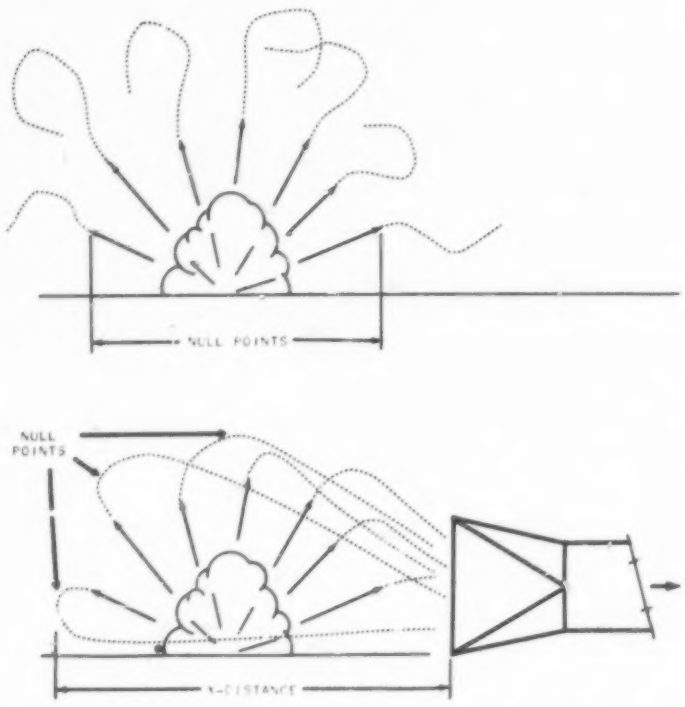


Figure 8. Location of null point and x-distance (Hemeon, 1955).

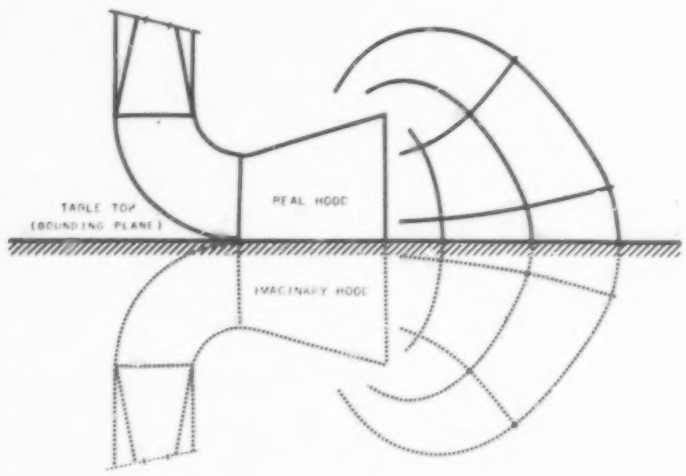


Figure 7. Rectangular hood bounded by a plane surface (Hemeon, 1955).

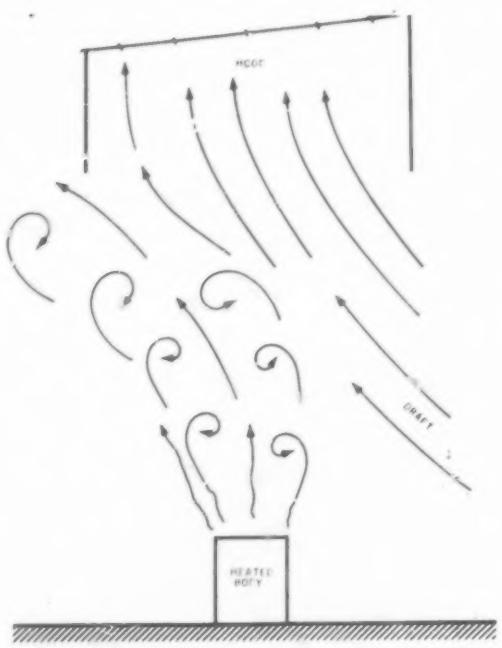


Figure 9. Drafts divert the rising column of air and prevent its capture by the hood (Hemeon, 1955).

or more periodically, and draft velocities of 500 to 600 fpm are not unusual in many cases. Drafts such as these may prevent capture of air contaminants by exterior hoods, as illustrated in Figure 9 for the case of a high-canopy hood, unless adequate baffling is provided or hood volume is increased to unreasonable values. Baffling provides, in effect, an enclosure that is almost always the most efficient hooding.

DESIGN OF HOODS FOR COLD PROCESSES

A large body of recommended ventilation rates has been built up over the years by various groups and organizations who are concerned with the control of air contaminants. This type of data is illustrated in Table 3. The use of these recommended values greatly simplifies hooding design for the control of many common air pollution problems. Note that almost all published recommendations have specified complete or nearly complete enclosure. These published data provide a reliable guide for the design engineer. The recommended values must, however, be adjusted to specific applications that depart from the assumed normal conditions.

Table 3. EXHAUST REQUIREMENTS FOR VARIOUS OPERATIONS

Operation	Exhaust arrangement	Remarks
Abrasive blast rooms	Tight enclosures with air inlets (generally in roof)	For 60 to 100 fpm downdraft or 100 fpm crossdraft in room
Abrasive blast cabinets	Tight enclosure	For 500 fpm through all openings, and a minimum of 20 air changes per minute
Bagging machines	Booth or enclosure	For 100 fpm through all openings for paper bags; 200 fpm for cloth bags
Belt conveyors	Hoods at transfer points enclosed as much as possible	For belt speeds less than 200 fpm, V = 350 cfm/ft belt width with at least 150 fpm through openings. For belt speeds greater than 200 fpm, V = 500 cfm/ft belt width with at least 200 fpm through remaining openings
Bucket elevator	Tight casing	For 100 cfm/ft^2 of elevator casing cross-section (exhaust near elevator top and also vent at bottom if over 35 ft high)
Foundry screens	Enclosure	Cylindrical--400 fpm through openings, and not less than 100 cfm/ft^2 of cross-section; flat deck--200 fpm through openings, and not less than 25 cfm/ft^2 of screen area
Foundry shakeout	Enclosure	For 200 fpm through all openings and not less than 200 cfm/ft^2 of grate area with hot castings and 150 cfm/ft^2 with cool castings
Foundry shakeout	Side hood (with side shields when possible)	For 400 to 500 cfm/ft^2 grate area with hot castings and 350 to 400 cfm/ft^2 with cool castings
Grinders, disc and portable	Downdraft grilles in bench or floor	For 200 to 400 fpm through open face, but at least 150 cfm/ft^2 of plan working area
Grinders and crushers	Enclosure	For 200 fpm through openings
Mixer	Enclosure	For 100 to 200 fpm through openings
Packaging machines	Booth Downdraft Enclosure	For 50 to 100 fpm For 75 to 150 fpm For 100 to 400 fpm
Paint spray	Booth	For 100 to 200 fpm indraft, depending upon size of work, depth of booth, etc.
Rubber rolls (calendars)	Enclosure	For 75 to 100 fpm through openings
Welding (arc)	Booth	For 100 fpm through openings

Spray Booths

Spray booths of the open-face type are generally designed to have a face indraft velocity of 100 to 200 fpm. This is usually adequate to assure complete capture of all overspray, provided the spraying is done within the confines of the booth, and the spray gun is always directed towards the interior. It is a common practice, especially with large work pieces, to place the work a short distance in front of the booth face. The overspray deflected from the work may easily escape capture, particularly with a careless or inexperienced operator. If this situation is anticipated, the equipment designer can provide a velocity of 100 fpm at the farthest point to be controlled, as in the following illustrative problem.

Example 1

Given:

A paint spray booth 10 feet wide by 7 feet high. Work may be 5 feet in front of the booth face at times. Nearly draftless area requires 100 fpm at point of spraying.

Problem:

Determine the exhaust rate required.

Solution:

From equation 12, volume required =

$$V_t = v_x\left(\frac{10x^2 + 2A_f}{2}\right)$$

$$V_t = 100\left(\frac{(10)(5)^2 + (2)(7)(10)}{2}\right) = 19,500 \text{ cfm}$$

From equation 8, face velocity =

$$v_f = \frac{V_t}{A_f}$$

$$v_f = \frac{19,500}{(7)(10)} = 280 \text{ fpm}$$

When the spraying area is completely enclosed to form a paint spray room, the ventilation requirements are not greatly reduced over those for spraying inside an open-face booth. The reason for this is that a velocity of approximately 100 fpm must be provided through the room for the comfort and health of the operator.

Abrasive Blasting

Abrasive blasting booths are similar to spray booths except that a complete enclosure is always required. In addition, particularly for small booths (bench type), the ventilation rate must sometimes be increased to accommodate the air used for blasting. The volume of blasting air can be determined from the manufacturer's specifications. For a small blasting booth, this will usually be about 50 to 150 cfm. The following illustrative problem shows how the ventilation rate for this kind of equipment is calculated.

Example 2

Given:

A small abrasive blasting enclosure 4 feet wide by 3 feet high by 3 feet deep. Total open area equals 1.3 ft^2.

Problem:

Determine the exhaust rate required.

Solution:

From Table 3, ventilation required = 500 fpm through all openings but not less than 20 air changes per minute.

Volume at 500 fpm through all openings:

$$V_t = 500 \times 1.3 = 650 \text{ cfm}$$

Volume required for 20 air changes per minute:

$$V_t = 20 \times \text{volume of booth}$$

$$V_t = 20 \times 4 \times 3 \times 3 = 720 \text{ cfm}$$

Open-Surface Tanks

Open-surface tanks may be controlled by canopy hoods or by slot hoods, as illustrated in Figure 10. The latter are more commonly employed. The ventilation rates required for open-surface tanks may be taken from Table 4, which is a modification of the American Standards Association code Z 9.1. These values should be considered as minimum under conditions where no significant drafts will interfere with the operation of the hood. When slot hoods are employed the usual practice is to provide a slot along each long side of the tank. The slots are designed for a velocity of 2,000 fpm through the slot face at the required ventilation rate. For a tank with two parallel slot hoods, the ventilation rate required and the slot width b_s may be taken directly from Figure 11, which graphs the American Standards Association code Z 9.1.

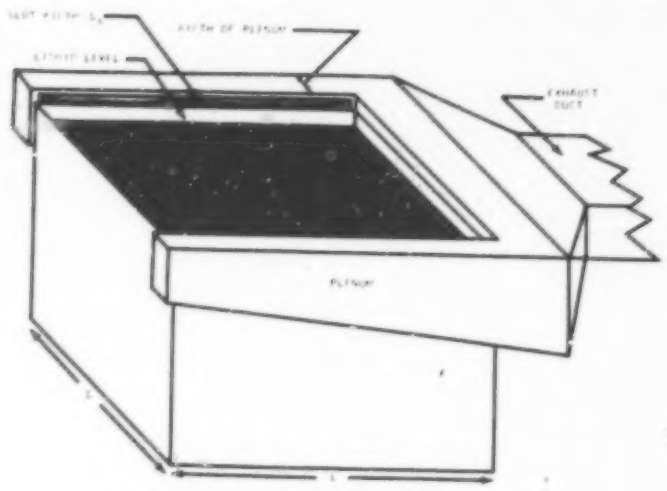


Figure 10. Slot hood for control of emissions from open-surface tanks (Adapted from Industrial Ventilation, 1960).

Neither the code nor Figure 11 makes allowance for drafts. The use of baffles is strongly recommended wherever possible to minimize the effect of drafts. If baffles cannot be used or are not sufficiently effective, the ventilation rate must be increased. The slot width is also increased to hold the slot face velocity in the range of 1,800 to 2,000 fpm.

The use of Figure 11 is illustrated in the following problem:

Example 3

Given:

A chrome plating tank, 2 feet wide by 3 feet long, to be controlled by parallel slot hoods along each of the 3-foot-long sides.

Problem:

Determine the total exhaust rate required and the slot width.

Solution:

From Figure 11, the ventilation rate required is 390 cfm per foot of tank length.

$$V_t = 390 \times 3 = 1,170 \text{ cfm}$$

From Figure 11, the slot width is $1\frac{1}{8}$ inches.

If a slot hood is used on only one side of a tank to capture emissions, and the opposite side of the tank is bounded by a vertical wall, Figure 11 can be used by assuming the tank to be half of a tank twice as wide having slot hoods on both sides. This procedure is illustrated below.

Example 4

Given:

The same tank as in Example 3, but a slot hood is to be installed along one side only. The other side is flush with a vertical wall.

Problem:

Determine the total exhaust rate and slot width required.

Solution:

The ventilation rate in cfm per foot of tank length is taken as half the rate for a tank twice as wide from Figure 11. Use width of 4 feet.

$$\frac{V_t}{L} = \frac{880}{2} = 440 \text{ cfm per foot}$$

Total exhaust volume required

$$V_t = 440 \times 3 = 1,320 \text{ cfm}$$

Slot width is read directly from Figure 11 for twice the width b_s = 2-5/8 inches.

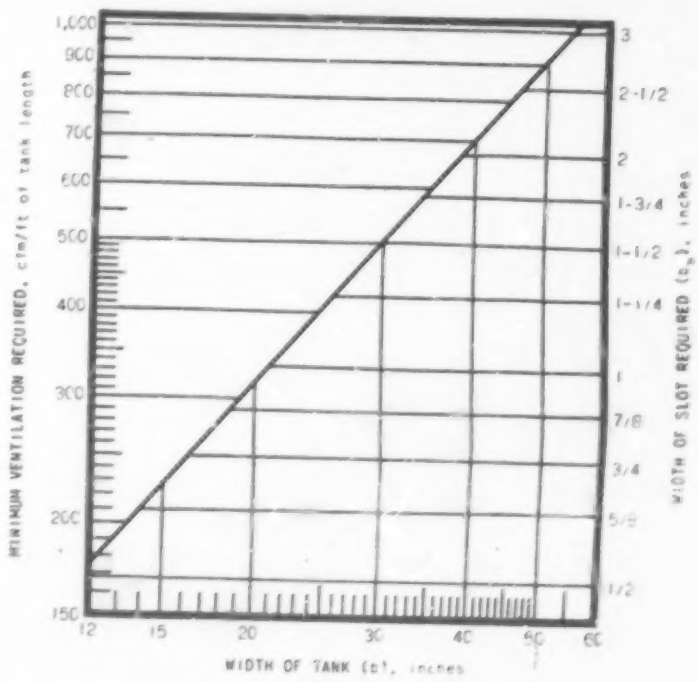


Figure 11. Minimum ventilation rates required for tanks.

Table 4. VENTILATION RATES FOR OPEN-SURFACE TANKS
(American Air Filter Company, Inc., 1964)

Process	Minimum ventilation rate, cfm per ft² of hood opening				Minimum ventilation rate,[a] cfm per ft² of tank area. Lateral exhaust W/L = tank width / tank length ratio					
	Enclosing hood		Canopy hood							
	One open side	Two open sides	Three open sides	Four open sides	W/L 00 to 0.24 A	W/L 00 to 0.24 B	W/L 0.25 to 0.49 A	W/L 0.25 to 0.49 B	W/L 0.50 to 1.0 A	W/L 0.50 to 1.0 B
Plating										
Chromium (chromic acid mist)	75	100	125	175	125	175	150	200	175	225
Arsenic (arsine)	65	90	100	150	90	130	110	150	130	170
Hydrogen cyanide	75	100	125	175	125	175	150	200	175	225
Cadmium	75	100	125	175	125	175	150	200	175	225
Anodizing	75	100	125	175	125	175	150	200	175	225
Metal cleaning (pickling)										
Cold acid	65	90	100	150	90	130	110	150	130	170
Hot acid	75	100	125	175	125	175	150	200	175	225
Nitric and sulfuric acids	75	100	125	175	125	175	150	200	175	225
Nitric and hydrofluoric acids	75	100	125	175	125	175	150	200	175	225
Metal cleaning (degreasing)										
Trichloroethylene	75	100	125	175	125	175	150	200	175	225
Ethylene dichloride	75	100	125	175	125	175	150	200	175	225
Carbon tetrachloride	75	100	125	175	125	175	150	200	175	225
Metal cleaning (caustic or electrolytic)										
Not boiling	65	90	100	150	90	130	110	150	130	170
Boiling	75	100	125	175	125	175	150	200	175	225
Bright dip (nitric acid)	75	100	125	175	125	175	150	200	175	225
Stripping										
Concentrated nitric acid	75	100	125	175	125	175	150	200	175	225
Concentrated nitric and sulfuric acids	75	100	125	175	125	175	150	200	175	225
Salt baths (molten salt)	50	75	75	125	60	90	75	100	90	110
Salt solution (Parkerise, Bonderise, etc.)										
Not boiling	90	90	100	150	90	130	110	150	130	170
Boiling	75	100	125	175	125	175	150	200	175	225
Hot water (if vent. desired)										
Not boiling	50	75	75	125	60	90	75	100	90	110
Boiling	75	100	125	175	125	175	150	200	175	225

[a]Column A refers to tank with hood along one side or two parallel sides when one hood is against a wall or a baffle running length of tank and as high as tank is wide; also to tanks with exhaust manifold along center line with W/2 becoming tank width in W/L ratio.

Column B refers to freestanding tank with hood along one side or two parallel sides.

DESIGN OF HOODS FOR HOT PROCESSES

Canopy Hoods

Circular high-canopy hoods

Hooding for hot processes requires the application of different principles than that for cold processes because of the thermal effect. When significant quantities of heat are transferred to the surrounding air by conduction and convection, a thermal draft is created that may cause a rising air current with velocities sometimes over 400 fpm. The design of the hood and the ventilation rate provided must take this thermal draft into consideration.

As the heated air stream rising from a hot surface moves upward, it mixes turbulently with the surrounding air. The higher the air column rises the larger it becomes and the more diluted with ambient air. Sutton (1950) investigated the turbulent mixing of a rising column of hot air above a heat source. Using data from experiments by Schmidt published in Germany, and his own experiments with military smoke generators, Sutton developed equations that describe the velocity and

diameter of a hot rising jet at any height above a hypothetical point source located a distance z below the actual hot surface. Hemeon adapted Sutton's equations to the design of high-canopy hoods for the control of air contaminants from hot sources. The rising air column illustrated in Figure 12 expands approximately according to the empirical formula

$$D_c = 0.5\ x_f^{0.88} \qquad (13)$$

where

D_c = the diameter of the hot column of air at the level of the hood face, ft

x_f = the distance from the hypothetical point source to the hood face, ft.

From Figure 12 it is apparent that x_f is the sum of y, the distance from hot source to the hood face, and z the distance below the hot source to the hypothetical point source. Values of z may be taken from Figure 13. According to Hemeon, the velocity of the rising column of air into the hood may be calculated from

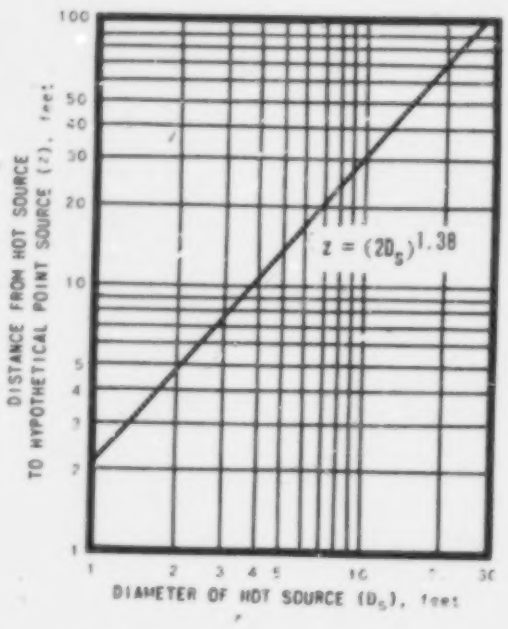


Figure 13. Value of z for use with high-canopy hood equations.

$$v_f = \frac{37}{x_f^{0.29}} (q_c)^{1/3} \qquad (14)$$

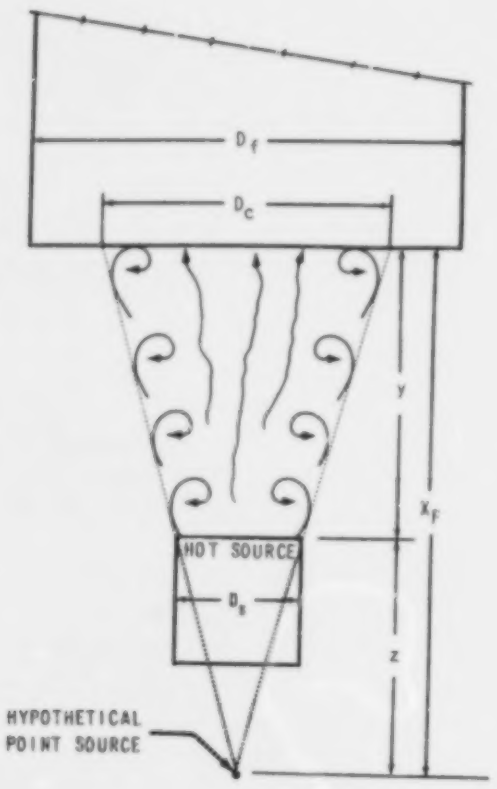


Figure 12. Dimensions used to design high-canopy hoods for hot sources (Hemeon, 1955).

where

v_f = the velocity of the hot air jet at the level of the hood face, fpm

x_f = the height of the hood face above the theoretical point source = y + z, ft

q_c = the rate at which heat is transferred to the rising column of air, Btu/min.

The rate at which heat is absorbed by the rising column may be calculated from the appropriate natural convection heat loss coefficient q_L listed in Table 5 and from the relationship

$$q_c = \frac{q_L}{60} A_s \Delta t \qquad (15)$$

where

q_c = the total heat absorbed by the rising air column, Btu/min

q_L = the natural convection heat loss coefficient listed in Table 5, Btu/ft^2 per hr per °F

A_s = the area of the hot source, ft^2

Δt = the temperature difference between the hot source and the ambient air, °F.

Table 5. COEFFICIENTS FOR CALCULATING SENSIBLE HEAT LOSS BY NATURAL CONVECTION (Hemeon, 1955)

Shape or disposition of heat surface	Natural convection heat loss (q_L) coefficient[a]
Vertical plates, over 2 ft high	$0.3\ (\Delta t)^{1/4}$
Vertical plates, less than 2 ft high (X = height in ft)	$0.28\ (\frac{\Delta t}{X})^{1/4}$
Horizontal plates, facing upward	$0.38\ (\Delta t)^{1/4}$
Horizontal plates, facing downward	$0.2\ (\Delta t)^{1/4}$
Single horizontal cylinders (where d is diameter in inches)	$0.42\ (\frac{\Delta t}{d})^{1/4}$
Vertical cylinders, over 2 ft high (same as horizontal)	$0.4\ (\frac{\Delta t}{d})^{1/4}$

Vertical cylinders less than 2 ft high. Multiply q_L from formula above by appropriate factor below:

Height, ft	Factor
0.1	3.5
0.2	2.5
0.3	2.0
0.4	1.7
0.5	1.5
1.0	1.1

[a]Heat loss coefficient, q_L is related to q_c as follows:

$$q_c = \frac{q_L}{60} A_s \Delta t$$

Schmidt's experiments were conducted in a closed laboratory environment designed to minimize drafts and other disturbances. Nevertheless, Sutton reports that there was a considerable amount of waver and fluctuation in the rising air column. In developing his equations, Sutton defined the horizontal limits of the rising air column as the locus of points having a temperature difference relative to the ambient atmosphere equal to 10 percent of that at the center of the column.

In view of the facts that this arbitrary definition does not truly define the outer limits of the rising air column and that greater effects of waver and drafts may be expected in an industrial environment, a safety factor should be applied in calculating the size of the hood required and the minimum ventilation rate to assure complete capture of the emissions. Since high-canopy hoods usually control emissions arising from horizontal-plane surfaces, a simplification can be derived by combining equations 14 and 15 with the heat transfer coefficient for horizontal-plane surfaces and allowing a 15 percent safety factor.

$$v_f = \frac{8(A_s)^{1/3}(\Delta t)^{5/12}}{x_f^{1/4}} \qquad (16)$$

Although the mean diameter of the rising air column in the plane of the hood face is determined from equation 13, the hood must be made somewhat larger in order to assure complete capture of the rising column of contaminated air as it wavers back and forth and is deflected by drafts. The exact amount of allowance cannot be calculated precisely, but factors that must be considered include the horizontal velocity of the air currents in the area, the size and velocity of the rising air jet, and the distance y of the hood above the hot

source. Other factors being equal, it appears most likely that the additional allowance for the hood size must be a function of the distance y. Increasing the diameter of the hood by a factor of 0.8 y has been recommended (Industrial Ventilation, 1960). The total volume for the hood can be calculated from

$$V_t = v_f A_c + v_r (A_f - A_c) \qquad (17)$$

where

V_t = the total volume entering the hood, cfm

v_f = the velocity of the rising air column at the hood face, fpm

A_c = the area of the rising column of contaminated air at the hood face, ft^2

v_r = the required velocity through the remaining area of the hood, $A_f - A_c$, fpm

A_f = the total area of the hood face, ft^2.

The value of v_r selected will depend upon the draftiness, height of the hood above the source, and the seriousness of permitting some of the contaminated air to escape capture. The value of this velocity is usually taken in the range of 100 to 200 fpm. It is recommended that a value less than 100 fpm not be used except under exceptional circumstances. The following problem illustrates the use of this method to design a high-canopy hood to control the emissions from a metal-melting furnace.

Example 5

Given:

A zinc-melting pot 4 feet in diameter with metal temperature 880°F. A high-canopy hood is to be used to capture emissions. Because of interference, the hood must be located 10 feet above the pot. Ambient air temperature is 80°F.

Problem:

Determine the size of hood and exhaust rate required.

Solution:

z = 11 feet from Figure 13 for 4-foot-diameter source

$$x_f = z + y$$

$$x_f = 11 + 10 = 21 \text{ feet}$$

Diameter of rising air stream at the hood face from Equation 13:

$$D_c = 0.5\, x_f^{0.88}$$

$$D_c = 0.5\,(21)^{0.88} = 7.3 \text{ feet}$$

Area of rising air stream at the hood face:

$$A_c = \frac{\pi}{4} D_c^2$$

$$A_c = (0.7854)(7.3)^2$$

$$= 42 \text{ square feet}$$

Hood size required--including increase to allow for waver of jet and effect of drafts:

$$D_f = D_c + 0.8y$$

$$D_f = 7.3 + (0.8)(10) = 15.3$$

Use 15-foot-4-inch-diameter hood

Area of hood face:

$$A_f = \frac{\pi}{4} (D_f)^2$$

$$A_f = (0.7854)(15.33)^2$$

$$= 185 \text{ square feet}$$

Velocity of rising air jet at hood face:

$$v_f = \frac{8\,(A_s)^{1/3}(\Delta t)^{5/12}}{x_f^{1/4}}$$

$$v_f = \frac{(8)(12.57)^{1/3}(800)^{5/12}}{(21)^{1/4}}$$

$$= 143 \text{ fpm}$$

Total volume required for hood:

$$V_t = v_f A_c + 100\,(A_f - A_c)$$

$$V_t = (143)(42) + (100)(185-42)$$

$$= 20,300 \text{ cfm}$$

If the hood could be lowered, the volume required to capture the emissions would be reduced substantially as illustrated below:

Example 6

Given:

The same furnace as in example problem No. 5, but the hood is lowered to 6 feet above the pot.

Problem:

Determine the size of hood and exhaust rate required.

Solution:

z = 11 feet from Figure 13 for 4-foot-diameter source

$$x_f = z + y$$

$$x_f = 11 + 6 = 17 \text{ feet}$$

Diameter of rising air stream at the hood face from equation 13.

$$D_c = 0.5\, x_f^{0.88}$$

$$D_c = 0.5\ (17)^{0.88} = 6.1 \text{ feet}$$

Area of the rising air stream at the hood face:

$$A_c = \frac{\pi}{4} (D_c)^2$$

$$A_c = (0.7854)(6.1)^2 = 29.2 \text{ square feet}$$

Hood size required:

$$D_f = D_c + 0.8\, y$$

$$D_f = (6.1) + (0.8)(6) = 10.9 \text{ feet}$$

Use 10-foot-11-inch-diameter hood

Area of the hood face:

$$A_f = \frac{\pi}{4} (D_f)^2$$

$$A_f = (0.7854)(10.92)^2 = 93.7 \text{ square feet}$$

Velocity of rising air jet at hood face:

$$v_f = \frac{8(A_s)^{1/3}(\Delta t)^{5/12}}{x_f^{1/4}}$$

$$v_f = \frac{(8)(12.57)^{1/3}(800)^{5/12}}{(17)^{1/4}} = 149 \text{ fpm}$$

Total volume required for hood:

$$V_t = v_f A_c + 100\,(A_f - A_c)$$

$$V_t = (149)(29.2) + (100)(93.7-29.2)$$

$$= 10,800 \text{ cfm}$$

Rectangular High-Canopy Hoods

The control of emissions from sources with other than circular shape may best be handled by hoods of appropriate shape. Thus, a rectangular source would require a rectangular hood in order to minimize the ventilation requirements. A circular hood used to control a rectangular source of emission would require an excessive volume. The method used to design a hood for a rectangular source is illustrated in example 7.

Example 7

Given:

A rectangular lead-melting furnace 2 feet 6 inches wide by 4 feet long. Metal temperature 700°F. A high-canopy hood is to be used located 8 feet above furnace. Assume 80°F ambient air.

Problem:

Determine the dimensions of the hood and the exhaust rate required.

Solution:

z = 6.2 from Figure 13 for 2.5-foot source

$$x_f = z + y = 6.2 + 8 = 14.2 \text{ feet}$$

The width of the rising air jet at the hood may be calculated from

$$D_c = 0.5\, x_f^{0.88}$$

$$D_c = 0.5\ (14.2)^{0.88} = 5.2 \text{ feet}$$

The length of the rising air jet may be assumed to be increased over that of the source the same amount as the width

$$D_c = (4) + (5.2 - 2.5) = 6.7 \text{ feet}$$

The area of the rising air jet is

$$A_c = (5.2)(6.7) = 35 \text{ square feet}$$

The hood must be larger than the rising air stream to allow for waver and drafts. By allowing 0.8 y for both width and length, the hood size is

Width = (5.2) + (0.8)(8) = 11.6 feet

Length = (6.7) + (0.8)(8) = 13.1 feet

Use hood 11 feet 7 inches wide by 13 feet 1 inch long

Area of hood:

$$A_f = (11.58)(13.083) = 152 \text{ square feet}$$

Velocity of rising air jet:

$$v_f = \frac{(8)(A_s)^{1/3}(\Delta t)^{5/12}}{x_f^{1/4}}$$

$$v_f = \frac{(8)(10)^{1/3}(620)^{5/12}}{(14.2)^{1/4}} = 130 \text{ fpm}$$

Total volume required for hood:

$$V_t = v_f A_c + v_r (A_f - A_c)$$

$$V_t = (130)(35) + (200)(152-35) = 28,000 \text{ cfm}$$

Note that in this problem a velocity of 200 fpm was used through the area of the hood in excess of the area of the rising air column. A larger value was selected for this case because lead fumes must be captured completely to protect the health of the workers in the area.

Circular low-canopy hoods

The design of low-canopy hoods is somewhat different from that for high-canopy hoods. A hood may be considered a low-canopy hood when the distance between the hood and the hot source does not exceed approximately the diameter of the source, or 3 feet, whichever is smaller. A rigid distinction between low-canopy hoods and high-canopy hoods is not intended or necessary. The important distinction is that the hood is close enough to the source that very little mixing between the rising air column and the surrounding atmosphere occurs. The diameter of the air column may, therefore, be considered essentially equal to the diameter of the hot source. The hood need be larger by only a small amount than the hot source to provide for the effects of waver and deflection due to drafts. When drafts are not a serious problem, extending the nood 6 inches on all sides should be sufficient. This means that the hood face diameter must be taken as 1 foot greater than the diameter of the source. For rectangular sources, a rectangular hood would be provided with dimensions 1 foot wider and 1 foot longer than the source. Under more severe conditions of draft or toxic emissions, or both, a greater safety factor is required, which can be provided by increasing the size of the hood an additional foot or more or by providing a complete enclosure. A solution to the problem of designing low-canopy hoods for hot sources has been proposed by Hemeon (1955).

Although the hood is usually larger than the source, little error occurs if they are considered equal. The total volume for the hood may then be determined from the following equation obtained by rearranging terms in Hemeon's equation and applying a 15 percent safety factor.

$$V_t = 4.7 (D_f)^{2.33} (\Delta t)^{5/12} \qquad (18)$$

where

V_t = total volume for the hood, cfm

D_f = the diameter of the hood, ft

Δt = the difference between the temperature of the hot source and the ambient atmosphere, °F.

A graphical solution to equation 18 is shown in Figure 14. To use this graph, select a hood size 1 or 2 feet larger than the source. The total volume required for a hood D_f feet in diameter may then be read directly from the graph for the actual temperature difference Δt between the hot source and the surrounding atmosphere.

Example 8

Given:

A low-canopy hood is to be used to capture the emissions during fluxing and slagging of brass in a 20-inch-diameter ladle. The metal temperature during this operation will not exceed 2,350°F. The hood will be located 24 inches above the metal surface. Ambient temperature may be assumed to be 80°F.

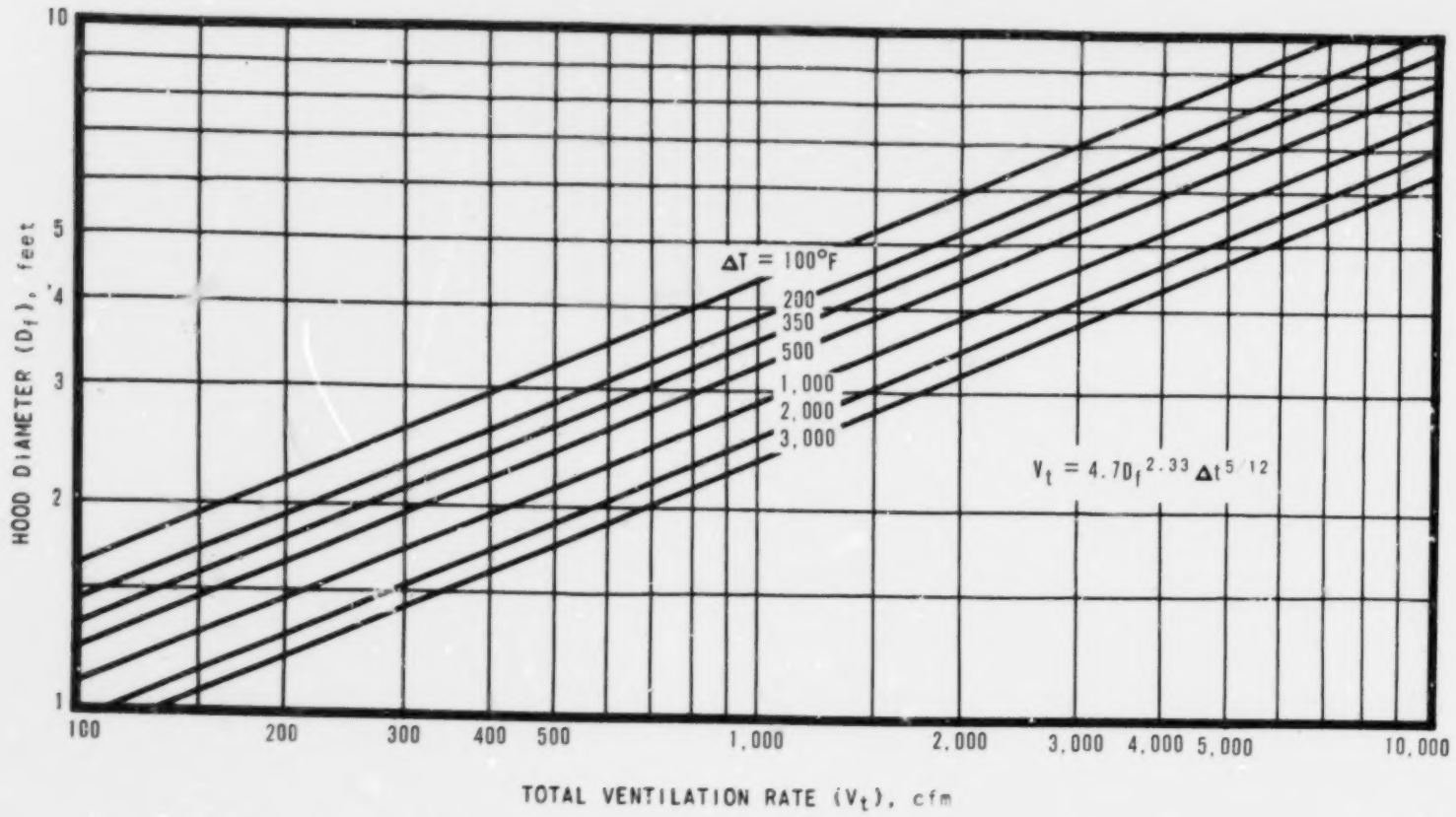


Figure 14. Minimum ventilation rates required for circular low-canopy hoods.

Problem:

Determine the size of hood and exhaust rate required.

Solution:

Temperature difference between hot source and ambient air:

$$\Delta t = 2,350 - 80 = 2,270°F$$

Use a hood diameter 1 foot larger than the hot source:

$$D_f = 1.67 + 1.0 = 2.67 \text{ feet}$$

Total exhaust rate required from Figure 14.

$$V_t = 1,150 \text{ cfm}$$

Rectangular low-canopy hoods

In a similar manner, Hemeon's equations for low-canopy hoods may be modified and simplified for application to rectangular hoods. With a 15 percent safety factor, the equation then becomes

$$\frac{V_t}{L} = 6.2\, b^{4/3}\, \Delta t^{5/12} \qquad (19)$$

where

V_t = the total volume for a low-canopy rectangular hood, cfm

L = the length of the rectangular hood (usually 1 to 2 feet larger than the source), ft

b = width of the rectangular hood (usually 1 to 2 feet larger than the source), ft

Δt = the temperature difference between the hot source and the surrounding atmosphere, °F.

Figure 15 is a graphical solution of equation 19. The use of this graph to design a low-canopy rectangular hood for a rectangular source is illustrated in example 9.

Example 9

Given:

A zinc die-casting machine with a 2-foot-wide by 3-foot-long holding pot for the molten zinc. A low-canopy hood is to be provided 30 inches above the pot. The metal temperature is 820°F. Ambient air temperature is 90°F.

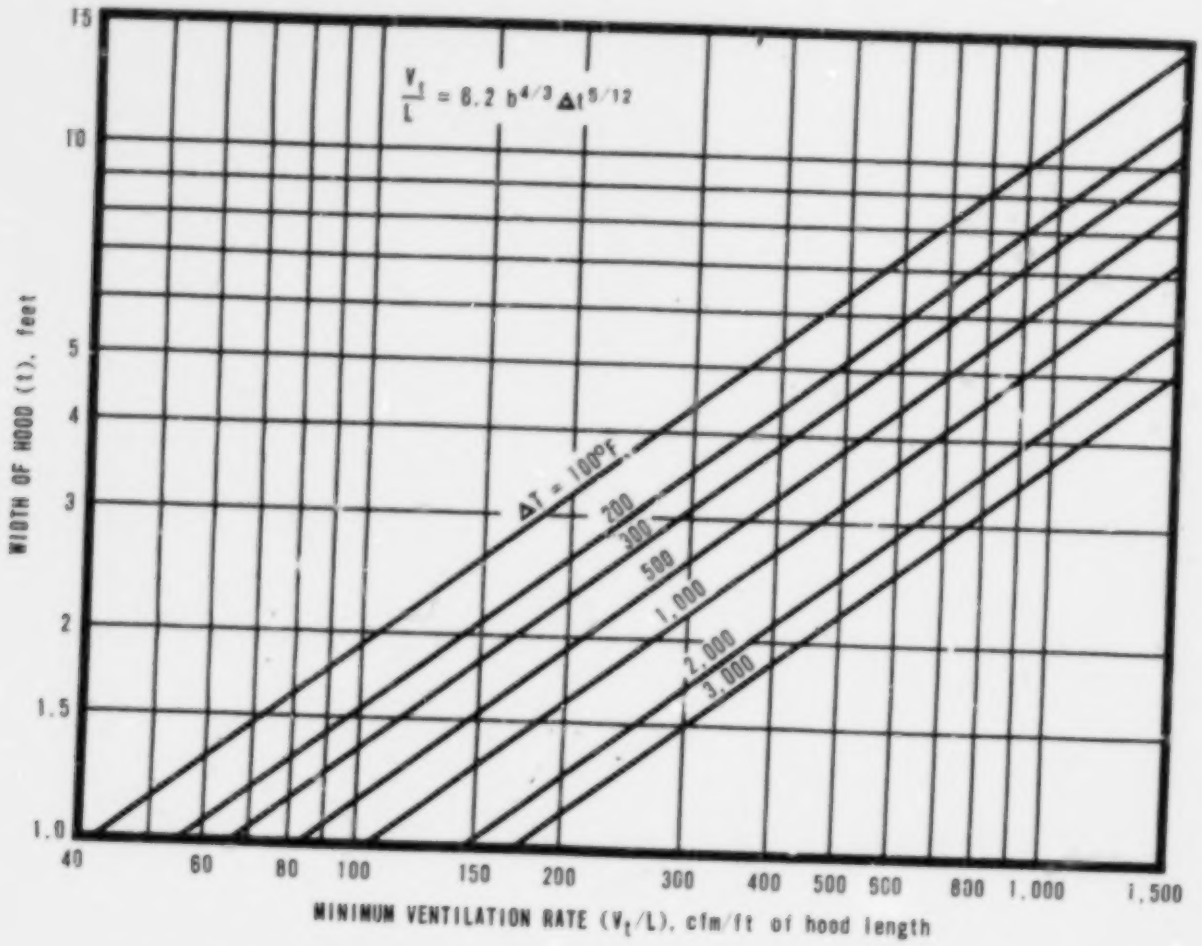


Figure 15. Minimum ventilation rates for rectangular low-canopy hoods.

Problem:

Determine hood size and exhaust rate required.

Solution:

Use a hood 1 foot wider and 1 foot longer than the source.

Hood size = 3 feet wide by 4 feet long.

Temperature difference between the hot source and ambient air:

$\Delta t = 820 - 90 = 730°F$

Exhaust rate required per foot of hood length from Figure 15.

$\frac{V_t}{L} = 430$ cfm/ft

Total exhaust rate required for hood:

$V_t = 430 \times 4 = 1,720$ cfm

Enclosures

A low-canopy hood with baffles is essentially the same as a complete enclosure. The exhaust rate for an enclosure around a hot source must, therefore, be based on the same principles as that for a low-canopy hood. Enclosures for hot processes cannot, however, be designed in the same manner as for cold processes. Here again, the thermal draft must be accommodated by the hood. Failure to do so will certainly result in emissions escaping from the hood openings. After determining the exhaust rate required to accommodate the thermal draft, calculate the hood face velocity or indraft through all openings. The indraft through all openings in the hood should not be less than 100 fpm under any circumstances. When air contaminants are released with considerable force, a minimum indraft velocity of 200 fpm should be provided. When the air contaminants are released with extremely great force as, for example, in a

direct-arc electric steel-melting furnace, an indraft of 500 to 800 fpm through all openings in the hood is required.

Specific Problems

Steaming tanks

When the hot source is a steaming tank of water, Hemeon (1955) develops a special equation by assuming a latent heat of 1,000 Btu per pound of water evaporated. He derives the following equation for the total volume required for a low-canopy hood venting a tank of steaming hot water.

$$V_t = 290 (W_s A_f D_t)^{1/3} \quad (20)$$

where

V_t = the total hood exhaust rate, cfm

W_s = the rate at which steam is released, lb/min

A_f = the area of the hood face, assumed approximately equal to the tank area, ft^2

D_t = the diameter for circular tanks or the width for rectangular tanks, ft.

Preventing leakage

Hoods for hot processes must be airtight. When leaks or openings in the hood above the level of the hood face occur, as illustrated in Figure 16, they will be a source of leakage owing to a chimney effect, unless the volume vented from the hood is substantially increased. Since openings may sometimes be unavoidable in the upper portions of an enclosure or canopy hood, a means of determining the amount of the leakage and the increase in the volume required to eliminate the leakage is necessary. Hemeon (1955) has developed an equation to determine the volume of leakage from a sharp-edge orifice in a hood at a point above the hood face.

$$v_e = 200\left(\frac{l_o q_c}{A_o (460 + t_m)}\right)^{1/3} \quad (21)$$

where

v_e = the velocity of escape through orifices in the upper portions of a hood, fpm

l_o = the vertical distance above the hood face to the location of the orifice, ft

q_c = the rate at which heat is transferred to the air in the hood from the hot source, Btu/min

A_o = the area of the orifice, ft^2

t_m = the average temperature of the air inside the hood, °F.

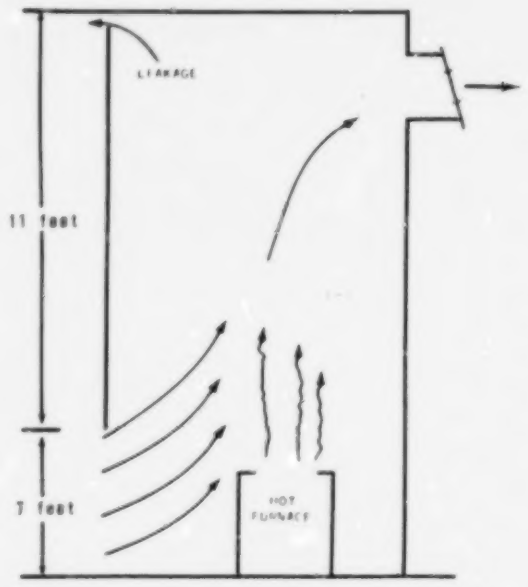


Figure 16. Illustration of leakage from top of hood (Hemeon, 1955).

A small amount of leakage can often be tolerated; however, if the emissions are toxic or malodorous, the leakage must be prevented completely. If all the cracks or openings in the upper portion of the hood cannot be eliminated, the volume vented from the hood must be increased so that the minimum indraft velocity through all openings including the hood face is in excess of the escape velocity through the orifice calculated by means of equation 21. The value of q_c may be determined by using the appropriate heat transfer coefficient from Table 5 together with equation 15 or by any other appropriate means. This method is illustrated in example 10.

Example 10

Given:

Several oil-fired crucible furnaces are hooded and vented as illustrated in Figure 16. The enclosure is 20 feet long. It is not possible to prevent leakage at the top of the enclosure. Total area of the leakage openings is 1 square foot. The fuel rate is 30 gallons per hour and the heating value is 140,000 Btu per gallon. Assume 80°F ambient air and 150°F average temperature of gases in the hood.

Problem:

Determine the minimum face velocity and total exhaust rate required to prevent leakage of contaminated air through the upper openings by assuming all openings are sharp-edge orifices.

Solution:

The rate of heat generation:

$$q_c = 30 \frac{gal}{hr} \times 140,000 \frac{Btu}{gal} \times \frac{1}{60}$$

$$= 70,000 \frac{Btu}{min}$$

Total open area:

$$A_o = (20 \times 7) + 1 \qquad = 141 \text{ ft}^2$$

The escape velocity through the leakage orifice:

$$v_e = 200 \left(\frac{1_o \, q_c}{A_o \, (460 + t_m)} \right)^{1/3}$$

$$v_e = 200 \left(\frac{(11)(70,000)}{141 \, (460 + 150)} \right)^{1/3} = 420 \text{ fpm}$$

The required exhaust rate:

$$V_t = v_e \, A_o$$

$$V_t = (420)(141) \qquad = 59,000 \text{ cfm}$$

Check mean hood air temperature:

Since $q_c = V_t \, \rho \, c_p \Delta t$:

where

ρ = average density of mixture, 0.075 lb/ft^3

c_p = average specific heat of mixture, 0.24 Btu/lb per °F

Δt = average hood temperature minus ambient air temperature.

$$\Delta t = \frac{70,000}{(59,000)(0.075)(0.24)} = 66°F$$

$$\Delta t_m = 80 + 66 \qquad = 146°F$$

This adequately approximates the original assumption.

HOOD CONSTRUCTION

If air temperature and corrosion problems are not severe, hoods are usually constructed of galvanized sheet metal. As with elbows and transitions, the metal should be at least 2 gauges heavier than the connecting duct. Reinforcement with angle iron and other devices is required except for very small hoods.

High-Temperature Materials

For elevated temperatures up to approximately 900°F, black iron may be employed, the thickness of the metal being increased in proportion to the temperature. For temperatures in the range of 400 to 500°F, 10-gauge metal is most commonly employed. When the temperature of the hood is as high as 900°F, the thickness of the metal may be increased up to 1/4 inch. Over 900°F, up to about 1,600 to 1,800°F, stainless steel must be employed. If the hood temperature periodically exceeds 1,800°F or is in excess of 1,600°F for a substantial amount of the time, refractory materials are required.

Corrosion-Resistant Materials

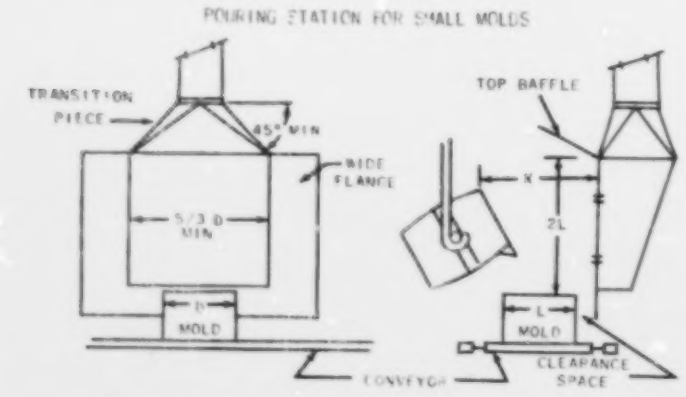
A variety of materials are available for corrosive conditions. Plywood is sometimes employed for relatively light duty or for temporary installations. A rubber or plastic coating may sometimes be applied on steel. Some of these coatings can be applied like ordinary paint. If severe corrosion problems exist, hoods must be constructed of sheets of PVC (polyvinyl chloride), fiberglas, or transite.

Design Proportions

Although the items of primary importance in designing hoods are the size, shape, and location of the hood face, and the exhaust rate, the depth of the hood and the transition to the connecting duct must also be considered. A hood that is too shallow is nothing more than a flanged-duct opening. On the other hand, excessive depth increases the cost without serving a useful purpose.

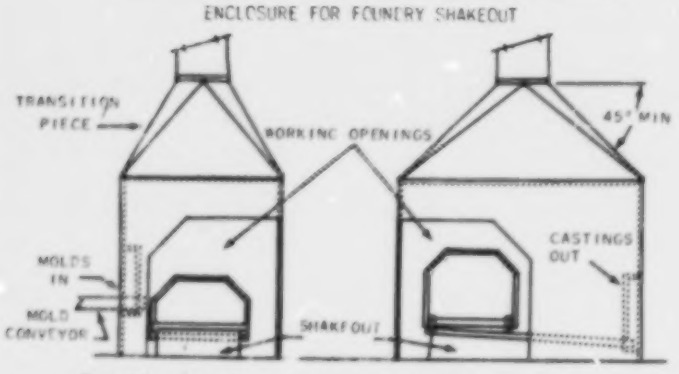
Transition to Exhaust Duct

It is desirable to have a transition piece between the hood and the exhaust system ductwork that is cone shaped with an included angle of 60° or less. This can often be made a part of the hood itself. The exact shape of the transition is the most important factor in determining the hood orifice losses. Examples of good practice in this regard are illustrated in Figure 17.



$V = 200(10X^2 + A)$

where V = minimum ventilation rate, cfm
X = distance between hood and ladle, ft
A = face area of hood, ft^2



Provide a minimum indraft of 200 cfm per square foot of obening but not less than 200 cfm per square foot of grate area for hot castings.

Figure 17. Examples of good hood design. Note use of enclosure, flanges, and transitions (Industrial Ventilation, 1960).

DUCT DESIGN

The design of hoods and the determination of exhaust volumes have been considered. Now the design of the ductwork required to conduct the contaminants to a collection device will be discussed. Calculations of pressure drop, system resistance, system balance, and duct construction will be covered.

GENERAL LAYOUT CONSIDERATIONS

Before designing and installing an exhaust system, try to group together the equipment to be served in order to make the system as small and compact as possible and thereby reduce the resistance load and power required. Extending an exhaust system to reach an isolated hood or enclosure is usually costly in regard to power consumption, and if the isolated hood cannot be located close to the main exhaust system, the installation of a separate system to care for the isolated equipment is probably preferable, in terms of operating economy.

When long rows of equipment must be served, the main header duct should be located as near as possible to the center of the group of equipment in order to equalize runs of branch duct. Where necessary, the equipment should be divided into subgroups and subheaders located to provide good distribution of airflow in the duct system, and proper velocities at the hood and enclosure inlets.

Air flowing in ducts encounters resistance due to friction and dynamic losses. Friction losses occur from the rubbing of the air along the surface of the duct, whereas dynamic losses occur from air turbulence due to rapid changes in velocity or direction. From Bernoulli's theorem, the sum of the static and velocity pressure upstream is equal to the sum of the static and velocity pressure plus the friction and dynamic losses downstream. A fan is normally required to provide sufficient static pressure to overcome the resistance of the system.

TYPES OF LOSSES

The losses in an exhaust system may be expressed as inertia losses, orifice losses, straight-duct friction losses, elbow and branch entry losses, and contraction and expansion losses. In addition to losses from the ductwork, there are also pressure losses through the air pollution collection equipment.

Inertia Losses

Inertia losses may be defined as the energy required to accelerate the air from rest to the velocity in the duct. In effect, they are the velocity pressure. Many other losses are expressed in terms of velocity pressure, but velocity pressure itself represents the energy of acceleration. It is calculated by equation 5, set forth earlier. By this equation, values of velocity pressure versus velocity have been calculated, as shown in Table 6.

Orifice Losses

The pressure or energy losses at the hood or duct entrances vary widely depending on the shape of the entrance. The losses are due mainly to the vena contracta at the hood throat. They are usually expressed as a percentage of the velocity pressure corresponding to the velocity at the hood throat. The losses vary from 1.8 h_v for a sharp-edge orifice to nearly zero for a well-rounded bell-mouth entry. Losses for common shapes of entries are given in Figure 18. Most complicated entries can be broken down into two or more simple entries, and the total entry loss computed by adding the individual losses.

Table 6. TABLE FOR CONVERSION OF VELOCITY(v_a) TO VELOCITY PRESSURE (h_v)

v_a, fpm	h_v, in. WC	v_a, fpm	h_v, in. WC
400	0.010	3,400	0.720
500	0.016	3,500	0.764
600	0.022	3,600	0.808
700	0.031	3,700	0.853
800	0.040	3,800	0.900
900	0.051	3,900	0.948
1,000	0.062	4,000	0.998
1,100	0.075	4,100	1.049
1,200	0.090	4,200	1.100
1,300	0.105	4,300	1.152
1,400	0.122	4,400	1.208
1,500	0.140	4,500	1.262
1,600	0.160	4,600	1.319
1,700	0.180	4,700	1.377
1,800	0.202	4,800	1.435
1,900	0.225	4,900	1.496
2,000	0.249	5,000	1.558
2,100	0.275	5,100	1.621
2,200	0.301	5,200	1.685
2,300	0.329	5,300	1.751
2,400	0.359	5,400	1.817
2,500	0.389	5,500	1.886
2,600	0.421	5,600	1.955
2,700	0.454	5,700	2.026
2,800	0.489	5,800	2.098
2,900	0.524	5,900	2.170
3,000	0.561	6,000	2.244
3,100	0.599	6,100	2.320
3,200	0.638	6,200	2.397
3,300	0.678		

Straight-Duct Friction Losses

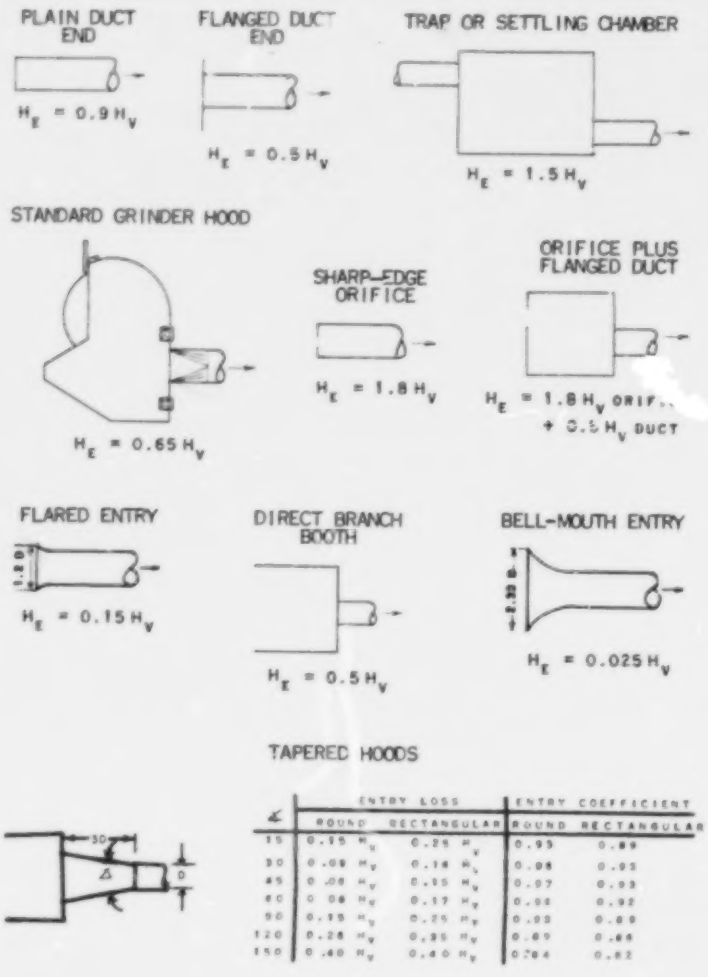
Many charts have been developed that give the friction losses in straight ducts. Most of these charts are based on new, clean duct. A resistance chart in which allowance has been made for moderate roughness of the duct is shown in Figure 19. Most exhaust systems collecting appreciable amounts of air contaminants are believed to reach at least this degree of roughness in a relatively short time after being placed in operation. Friction loss in inches of water per 100 feet of duct is plotted in terms of duct diameter, velocity, and volume. If any two of these quantities are given, the other two can be read from the chart.

Elbow and Branch Entry Losses

The simplest way to express resistance of elbows and branch entries is in equivalent feet of straight duct of the same diameter that will have the same pressure loss as the fitting. The equivalent lengths are added to the actual lengths of straight duct, and the resistance for each run computed from Figure 19. Equivalent lengths of elbows and entries are given in Table 7.

Exhaust system calculator

Most of the charts, tables, and equations have been incorporated into a single sliderule device, as illustrated in Figure 20. The upper scales on the front side will give friction losses just as in Figure 19. Velocity pressure can be read from the same scales by setting 4,000 on the velocity scale opposite 1.00 on the friction scale. Then, opposite any other velocity, the friction scale will give the correct velocity pressure. The lower scales perform volume and velocity calculations for a given duct diameter. Temperature correction scales and a duct condition correction scale are provided. On the reverse side (not shown in Figure 20), equivalent lengths for elbows, branch entries, and weather caps are given. On the lower portion of each side, hood entry losses are given for all the usual entry shapes.



α	ENTRY LOSS ROUND	ENTRY LOSS RECTANGULAR	ENTRY COEFFICIENT ROUND	ENTRY COEFFICIENT RECTANGULAR
15	0.15 H_V	0.25 H_V	0.95	0.89
30	0.09 H_V	0.16 H_V	0.96	0.93
45	0.08 H_V	0.15 H_V	0.97	0.93
60	0.08 H_V	0.17 H_V	0.96	0.92
90	0.15 H_V	0.25 H_V	0.93	0.89
120	0.28 H_V	0.35 H_V	0.89	0.86
150	0.40 H_V	0.40 H_V	0.84	0.82

Figure 18. Hood entry losses (Adapted from Industrial Ventilation, 1956).

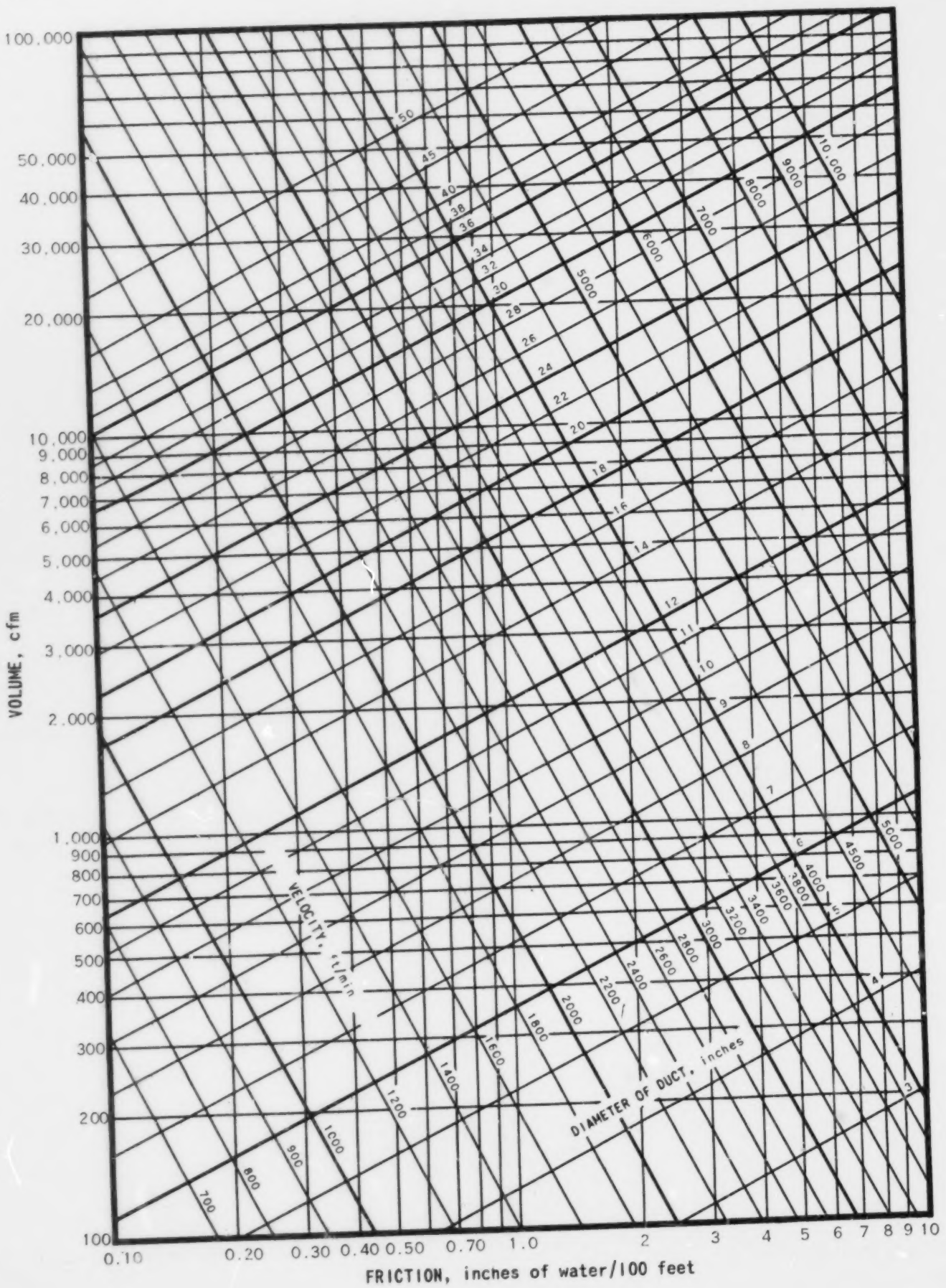
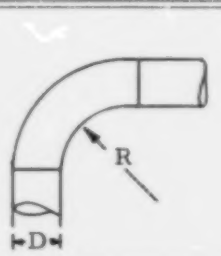
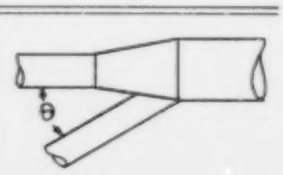


Figure 19. Friction loss chart.

Table 7. AIR FLOW RESISTANCE CAUSED BY ELBOWS AND BRANCH ENTRIES EXPRESSED AS EQUIVALENT FEET OF STRAIGHT DUCT
(Adapted from Industrial Ventilation, 1956)





Diameter of duct, in.	90° Elbow Throat radius (R)			60° Elbow Throat radius (R)			45° Elbow Throat radius (R)			Branch entry Angle of entry (θ)		
	1.0 D	1.5 D	2.0 D	1.0 D	1.5 D	2.0 D	1.0 D	1.5 D	2.0 D	45°	30°	15°
3	5	4	3	4	3	2	2	1	1	3	2	1
4	7	5	4	5	4	3	4	3	2	5	3	1
5	9	6	5	7	5	4	5	4	3	6	4	2
6	11	7	6	8	5	4	6	4	3	7	5	2
7	12	9	7	9	6	5	7	5	4	9	6	3
8	14	10	8	11	7	6	8	5	4	11	7	3
9	17	12	10	12	9	7	9	6	5	12	8	4
10	20	13	11	14	10	8	10	7	6	14	9	4
11	23	16	13	17	12	10	11	8	6	15	10	5
12	25	17	14	20	13	11	12	9	7	18	11	5
14	30	21	17	23	16	13	14	10	8	21	13	6
16	36	24	20	27	18	15	17	12	10	25	15	8
18	41	28	23	32	22	18	20	13	11	28	18	9
20	46	32	26	36	24	20	23	16	13	32	20	10
22	53	37	30	39	27	22	27	18	15	36	23	11
24	59	40	33	44	30	25	30	20	16	40	25	13
26	64	44	36	48	33	27	32	22	18	44	28	14
28	71	49	40	52	35	29	35	24	20	47	30	15
30	75	51	42	55	38	31	37	26	21	51	32	16
36	92	63	52	68	46	38	46	32	26	-	-	-
40	105	72	59	75	51	42	52	35	29	-	-	-
48	130	89	73	91	62	51	64	44	36	-	-	-

Contraction and Expansion Losses

When the cross-sectional area of a channel through which a gas is flowing contracts, a pressure loss is encountered. The magnitude of the loss depends upon the abruptness of the contraction. When the cross-sectional area expands, a portion of the decrease in velocity pressure may be converted into static pressure. The increase or decrease in pressure from expansion and contraction can be calculated from the diagrams and formulas given in Tables 8 and 9. Losses from small changes in velocity can be neglected.

Collection Equipment

Pressure through collection equipment varies widely. Most manufacturers supply data on pressure drop for their equipment. In the absence of data, resistances are usually estimated by comparing them with known values for similar equipment. In collectors such as cyclones and scrubbers where the velocities are high, pressure varies approximately with the square of the velocity. If the loss is known at one velocity, the loss at any other velocity is computed by multiplying by the square of the ratio of the velocities. In cloth filter dust collectors, however, the flow is laminar, and pressure drop varies approximately as the first power of the velocity ratios.

DESIGN PROCEDURES

Methods of Calculation

The first step in designing an exhaust system is to determine the volume of air required at each hood or enclosure to ensure complete collection

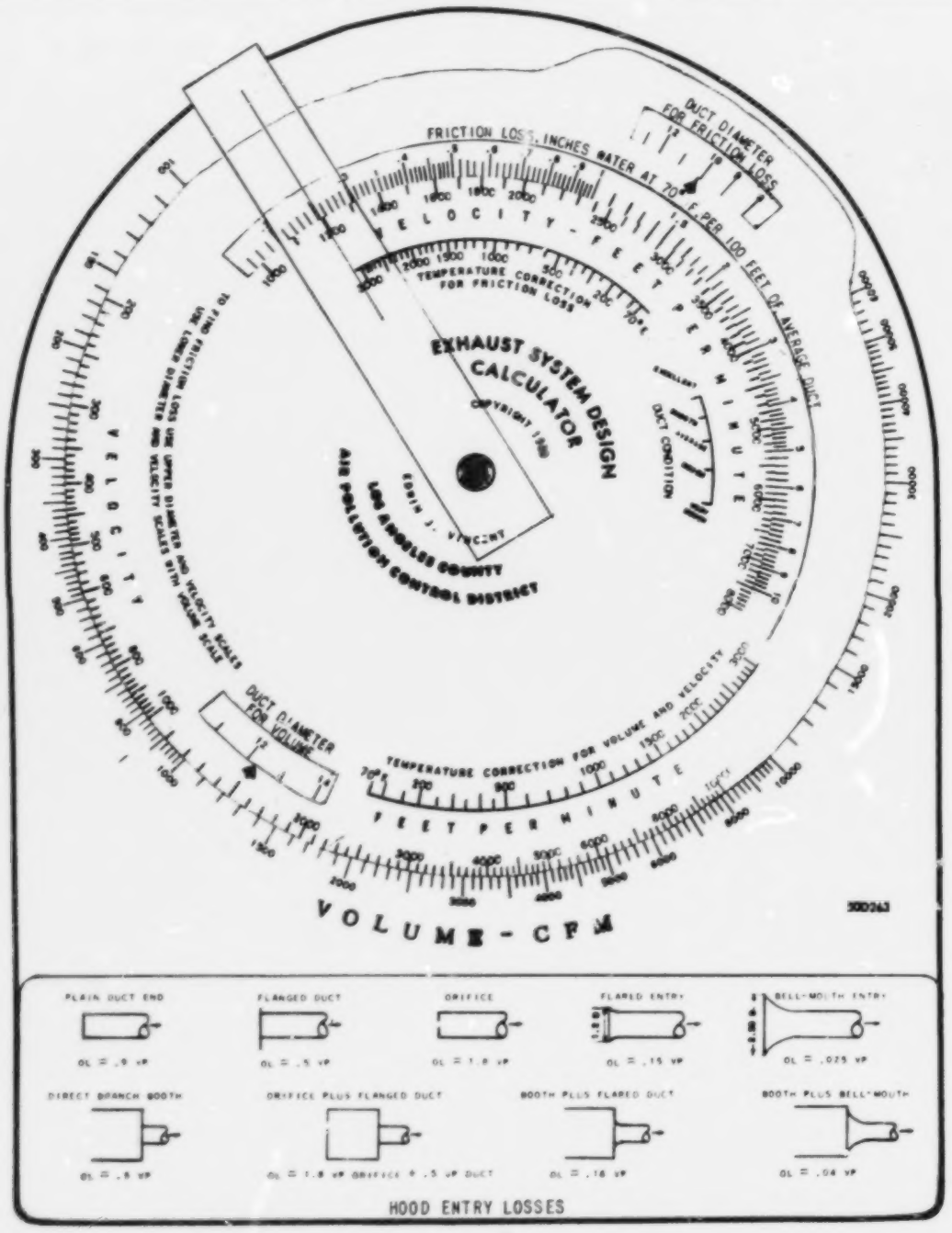

FRICTION LOSS, INCHES WATER AT 70° F. PER 100 FEET OF AVERAGE DUCT
DUCT DIAMETER FOR FRICTION LOSS
VELOCITY - FEET PER MINUTE
TEMPERATURE CORRECTION FOR FRICTION LOSS
EXHAUST SYSTEM DESIGN CALCULATOR
COPYRIGHT 1960
EDWIN J. VINCENT
LOS ANGELES COUNTY AIR POLLUTION CONTROL DISTRICT
DUCT CONDITION
TO FIND FRICTION LOSS USE UPPER DIAMETER AND VELOCITY SCALES
TO FIND VELOCITY LOSS USE LOWER DIAMETER AND VELOCITY SCALES WITH VOLUME SCALE
VELOCITY
DUCT DIAMETER FOR VOLUME
TEMPERATURE CORRECTION FOR VOLUME AND VELOCITY
FEET PER MINUTE
VOLUME - CFM
300263
PLAIN DUCT END
FLANGED DUCT
ORIFICE
FLARED ENTRY
BELL-MOUTH ENTRY
OL = .9 VP
OL = .5 VP
OL = 1.8 VP
OL = .15 VP
OL = .025 VP
DIRECT BRANCH BOOTH
ORIFICE PLUS FLANGED DUCT
BOOTH PLUS FLARED DUCT
BOOTH PLUS BELL-MOUTH
OL = .5 VP
OL = 1.8 VP ORIFICE + .5 VP DUCT
OL = .16 VP
OL = .04 VP
HOOD ENTRY LOSSES

Figure 20. Exhaust system calculator.

of the air contaminants, by using the principles given previously. The required conveying velocity is then determined from the nature of the contaminant. Table 10 can be used in determining conveying velocities.

The branch duct and header diameters are then calculated to give the minimum conveying velocity. When the calculated diameter lies between two available diameters, the smaller diameter should be chosen to ensure an adequate conveying velocity. The duct layout is then completed, and the lengths of ducts and number and kinds of fittings determined. The system resistance can then be computed. The calculations can be most easily accomplished by using a tabular form such as those shown later.

Methods of Design

In designing a system of ductwork with multiple branches, the resistance of each branch must be adjusted so that the static pressure balance, which exists at the junction of two branches, will give the desired volume in each branch. In general, two methods of accomplishing this result are used:

1. The balanced-duct or static pressure balance method, in which duct sizes are chosen so that the static-pressure balance at each junction will achieve the desired air volume in each branch duct.
2. The blast gate adjustment method, in which calculations begin at the branch of greatest resistance. The other branches are merely sized

to give the minimum required velocity at the desired volume. Blast gates are provided in each branch, and after construction, the gates are adjusted to give the desired volume in each branch duct.

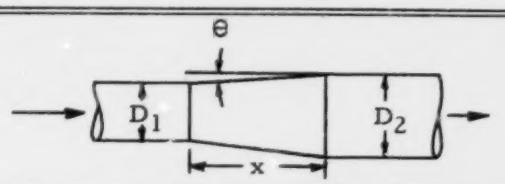
The balanced-duct system is less flexible and more tedious to calculate, but it has no blast gates that might collect deposits or be tampered with by unauthorized persons. Layout must be in complete detail and construction must follow layout exactly.

The blast gate system has more flexibility for future changes and is easier to calculate; volumes can be adjusted within certain ranges, and duct location is not so critical.

Calculation Procedures

The balanced-duct method: The calculations for a balanced-duct system start at the branch of greatest resistance. Using the duct size that will give the required volume at the minimum conveying velocity, calculate the static pressure up to the junction with the next branch. The static pressure is then calculated along this next branch to the same junction. If the two calculations agree within 5 percent, the branches may be considered in balance.

Table 8. DUCTWORK DESIGN DATA SHOWING STATIC PRESSURE LOSSES AND REGAINS[a] THROUGH ENLARGING DUCT TRANSITIONS
(Industrial Ventilation, 1962)



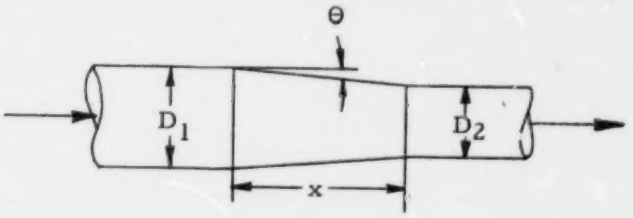
Taper angle (θ), degrees	$\frac{x}{D_2 - D_1}$	Regain factor (R)	Loss factor (L)
3-1/2	8.13	0.78	0.22
5	5.73	0.72	0.28
10	2.84	0.56	0.44
15	1.86	0.42	0.58
20	1.38	0.28	0.72
25	1.07	0.13	0.87
30	0.87	0.00	1.00
over 30		0.00	1.00

[a]The regain and loss factors are expressed as a fraction of the velocity pressure difference between points (1) and (2). In calculating the static pressure changes through an enlarging duct transition, select R from the table and substitute in the equation

$$SP_2 = SP_1 + R(h_{v_1} - h_{v_2})$$

where h_v is (+)
SP is (+) in discharge duct from fan
SP is (-) in inlet duct to fan

Table 9. DUCTWORK DESIGN DATA SHOWING CONTRACTION PRESSURE LOSSES THROUGH DECREASING DUCT TRANSITIONS
(Industrial Ventilation, 1956)



Taper angle (θ), degrees	$\frac{x}{D_1 - D_2}$	Loss fraction (L) of h_v difference	For abrupt contraction (θ > 60°)	
			Ratio D_2/D_1	Factor K
5	5.73	0.05	0.1	0.48
10	2.84	0.06	0.2	0.46
15	1.86	0.08	0.3	0.42
20	1.38	0.10	0.4	0.37
25	1.07	0.11	0.5	0.32
30	0.87	0.13	0.6	0.26
45	0.50	0.20	0.7	0.20
60	0.29	0.30		
SP change: $SP_2 = SP_1 - (h_{v_2} - h_{v_1}) - L(h_{v_2} - h_{v_1})$			SP change: $SP_2 = SP_1 - (h_{v_2} - h_{v_1}) - K(h_{v_2})$	

Table 10. RECOMMENDED MINIMUM DUCT VELOCITIES
(Brandt, 1947)

Nature of contaminant	Examples	Duct velocity, fpm
Gases, vapors, smokes, fumes, and very light dusts	All vapors, gases, and smokes; zinc and aluminum oxide fumes; wood, flour, and cotton lint	2,000
Medium-density dry dust	Buffing lint; sawdust; grain, rubber, and plastic dust	3,000
Average industrial dust	Sandblast and grinding dust, wood shavings, cement dust	4,000
Heavy dusts	Lead, and foundry shakeout dusts; metal turnings	5,000

If the difference in static pressure is more than 20 percent, a smaller diameter duct should be used in the branch with the lower pressure drop to increase its resistance. When the difference in pressure loss in the two branches is between 5 and 20 percent, balance can be obtained by increasing the flow in the branch with the lower loss. Since pressure losses increase as the square of the volume, the increased volume can be readily calculated as:

$$\text{Corrected cfm} = \sqrt{\frac{h_s \text{ larger}}{h_s \text{ lower}}} \qquad (22)$$

The pressure loss in the header is then calculated to the next branch. This branch is then sized to achieve a static pressure balance at this junction with the required volume (or slightly greater) in the branch duct. This procedure is continued until the discharge point of the system is reached.

The blast gate adjustment method: The calculations for a system to be balanced by blast gate adjustment also start at the branch of greatest resistance and proceed to the header. Pressure losses are then calculated only along the header. Pressure drops in the remaining branches are not calculated except when calculation is deemed advisable in order to check a branch to be sure its pressure drop does not exceed the static pressure at its junction with the header.

Fan Static Pressure

The preceding calculations are based on static pressure; that is, the balancing or governing pressures at the duct junctions are static pressures. Most fan-rating tables are given in terms of fan static pressure. The National Association of Fan Manufacturers defines the fan static pressure as the total pressure diminished by the velocity pressure at the fan outlet, or

$$\text{fan } h_s = \text{fan H} - h_v \text{ fan outlet} \qquad (23)$$

On the absolute pressure scale,

$$\text{fan H} = \text{H outlet} - \text{H inlet} \qquad (24)$$

Combining the two equations

$$\begin{aligned} \text{fan } h_s &= \text{H outlet} - \text{H inlet} - h_v \text{ outlet} \\ &= h_s \text{ outlet} + h_v \text{ outlet} - (h_s \text{ inlet} + h_v \text{ inlet}) \\ &\quad - h_v \text{ outlet} \\ &= h_s \text{ outlet} - h_s \text{ inlet} - h_v \text{ inlet} \end{aligned} \qquad (25)$$

Static pressures are nearly always measured relative to atmospheric pressure, and static pressure at the fan inlet is negative. In ordinary usage, only the numerical values are considered, in which case, equation 25 becomes

$$\text{fan } h_s = h_s \text{ outlet} + h_s \text{ inlet} - h_v \text{ inlet} \qquad (26)$$

In evaluating the performance of a fan, examine the tables to determine whether they are based on fan static pressure or on total pressure.

Balanced-Duct Calculations

A problem illustrating calculation by the balanced-duct method is worked out as follows. The given operation involves the blending of dry powdered materials. A sketch of the equipment is given in Figure 21. The equipment and ventilation requirements are presented in Tables 11 and 12.

A minimum conveying velocity of 3,500 fpm is to be maintained in all ducts. Elbows have a throat radius of 2 D. The balanced-duct method is to be used in the duct design. The detailed calculations are shown in Table 13. Calculations start at branch A. A 6-inch-diameter duct gives the nearest velocity to 3,500 fpm at the required volume of 750 cfm. The actual velocity of 3,800 fpm is entered in column 5, and the corresponding velocity pressure, in column 6. From Figure 19, the entry loss is 50 percent h_v, which is entered in column 7 left. The length of straight duct is entered in column 8. The equivalent length for the elbows is found in Table 7, and the sum is entered in column 9 right. The total equivalent length is then found by adding column 8 and column 9 right and entering the sum in column 11. The resistance per 100 feet of duct is then read from Figure 20 at 6-inch diameter and 3,800 fpm, and is entered in column 12. The resistance pressure (h_r) is calculated by multiplying column 11 by column 12 and dividing by 100. This value is entered in column 13. The static pressure is then the sum of the velocity pressure and the hood loss plus the resistance pressure, column 6 + column 7 right + column 13.

In branch B, a volume of 200 cfm is required. A 3-1/2-inch duct would give a velocity of 3,000 fpm, which is below the minimum. Hence the branch was calculated with a 3-inch duct at 4,000 fpm. The resulting h_s (column 14 left) was more than 20 percent greater than that for branch A. A 3-1/2-inch duct must, therefore, be used and the volume increased to 240 cfm to maintain the minimum velocity. At these conditions, the h_s values for the two branches are within 5 percent and may be considered in balance.

In section C, a 7-inch duct will carry the combined volume from branches A and B at the nearest velocity above the minimum. The only pressure drop

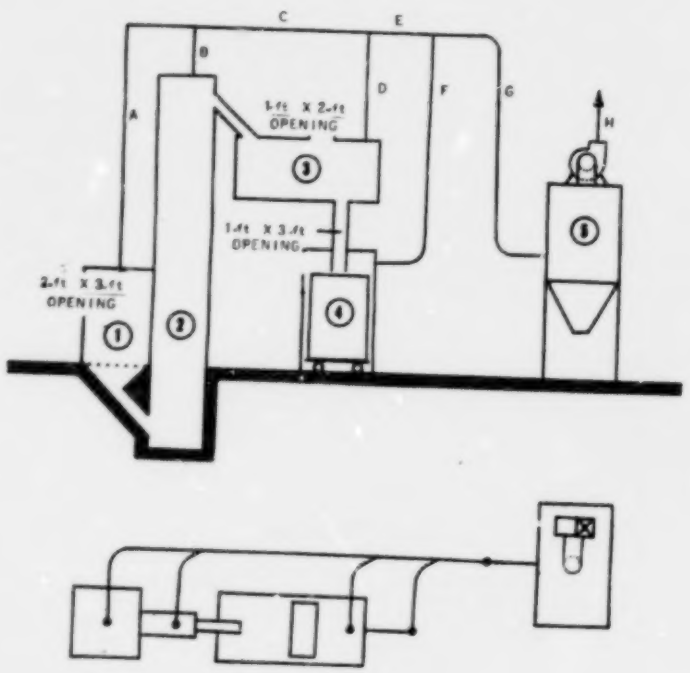


Figure 21. Sketch of exhaust system used in Table 11 showing duct design calculations by the balanced-duct method.

Table 11. EQUIPMENT AND VENTILATION REQUIREMENTS FOR BLENDING DRY POWDERED MATERIALS

Equipment	Ventilation requirement	Volume, cfm
Dump hopper (1), 2- by 3-ft opening	125-fpm indraft through opening	750
Bucket elevator (2), 1- by 2-ft casing	100 cfm per ft^2 of casing area	200
Ribbon blender (3), 1- by 2-ft opening	150-fpm indraft through opening	300
Drum-filling booth (4), 1- by 3-ft opening	200-fpm indraft through opening	600
Cloth filter dust collector (5) maximum resistance, 4 in. wg		

Table 12. DUCT LENGTHS AND FITTINGS REQUIRED IN BLENDING DRY POWDERED MATERIALS

Branch	Length, ft	Elbows, No. and degree	Entries, No. and degree
A	14	2, 90	
B	4	1, 60	1, 30
C	7		
D	6	1, 90	1, 30
		1, 60	
E	3		
F	11	2, 90	1, 30
		1, 60	
G	12	2, 90	

is due to the friction in the 7 feet of straight duct. This h_r is added to the h_s at the first junction. In branch D, 300 cfm is required, and this volume will give approximately 3, 450 fpm in a 4-inch duct. The resulting h_s is, however, about 20 percent lower than the h_s at the main. The cfm must, therefore, be increased by the ratio of the square roots of the static pressures, or from 300 to 350 cfm.

In main duct E, an 8-inch diameter duct will handle a volume of 1, 340 cfm at a velocity of 3, 800 fpm. An h_r of 0.10 inch WC is recorded in column 13, giving an h_s of 2.87 inches WC to the junction EF.

Calculation procedures for branch F are similar to those for branch E, and the required 600 cfm for the drum-filling booth must be increased to 640 cfm to obtain a static pressure balance at junction EF.

The total volume of 1, 980 cfm gives a velocity of 3, 600 fpm in a 10-inch-diameter main duct G to the baghouse. This run of duct and two 90° elbows have a resistance pressure of 0.88 inch WC, giving a total inlet static pressure of 7.75 inches WC, after the given resistance of the baghouse is added. The outlet static pressure is calculated similarly by calculating the resistance of the straight run of duct H. This static pressure of 0.21 inch WC is added to the inlet static pressure. The velocity pressure of 0.81 inch WC (one h_v at a velocity of 3, 600 fpm at the fan inlet) is subtracted from the above total static pressure to yield a fan static pressure of 7.15 inches WC.

Blast Gate Method

The same system can be designed by the blast gate adjustment method. The calculations are shown in Table 14. Branch A is calculated as before. Branches B, D, and F are calculated at or near the minimum conveying velocity so that the h_s drop in each does not exceed the h_s at the junction with the main. No adjustments are made in the volumes. Blast gates will be installed in each of these branches to provide the required increase in resistance.

CHECKING AN EXHAUST SYSTEM

The preceding example problem illustrates the calculations for designing an exhaust system. In checking plans for an exhaust system, use similar calculations but take a different approach. A system of ductwork with a specific exhauster is given and the problem is to determine the flow conditions that will exist.

The objectives of checking an exhaust system are:

1. To determine the exhaust volume and indraft velocity at each pickup point and evaluate the adequacy of contaminant pickup;

2. to determine the total exhaust volume and evaluate the size and performance of the collector or control device;

3. to determine the system's static pressure and evaluate the fan capacity, speed, and horsepower required;

4. to determine the temperature at all points in the system in order to evaluate the materials of construction of the ductwork and the collector.

Illustrative Problem

To illustrate a method of checking an exhaust system, another problem is worked. A line drawing of the ductwork is given in Figure 22. None of the calculations used in designing the system are given. Since no blast gates are shown, assume that the system was designed by the balanced-duct method.

Resistance calculations are presented in Table 15. This form was designed for maximum facility in checking an exhaust system. Calculations start at hood A with an assumed velocity (or volume) of 3, 500 fpm. The static pressure drop is then computed to junction C. Branch B-C is then computed with an assumed velocity of 3, 500 fpm. Since the h_s from this branch does not match that from branch A-C, the second velocity is corrected by multiplying by the square root of h_s A-C/h_s B-C. The corrected velocity is entered in column 14 and is used to compute the cfm, which is entered in column 15. The other branches are calculated in the same manner, that is, assume a velocity at the hood and correct it by the square root of the h_s ratio. Thus, all the calculations are related to the original assumption of velocity in the first branch.

Table 13. EXHAUST SYSTEM CALCULATIONS BY BALANCED-DUCT METHOD

1	2	3	4		5	6	7		8	9		10		11	12	13	14			15	16
No. of branch or main	Duct diam, in.	Gas temp, °F	Volume, cfm, Branch	Main	Velocity, fpm	One h_v at 70°F	Hood loss % h_v	Hood loss in. WC	Length straight duct, ft	Elbows No. and angle	Elbows Equivalent length, ft	Branch entry No. and angle	Branch entry Equivalent length, ft	Total equivalent length, ft	Resistance per 100 ft	h_F in. WC at 70°F	Static pressure[a] Branch at 70°F	Static pressure[a] Branch at T°F	Static pressure[a] Main	Cor. br. vel.	Temp in main, °F
A	6		750		3,800	0.90	50	0.45	14	2, 90°	12			26	4.5	1.17	2.52		2.52		
B	3		200		4,000	1.0	100	1.00	4	1, 90° 1, 60°	5	1, 30°	2	11	9.8	1.08	3.08		2.52		
			h_a difference greater than 20%, increase B to $3\frac{1}{2}$ diameter																		
B	$3\frac{1}{2}$		240		3,600	0.81	100	0.81	4	1, 90° 1, 60°	6	1, 30°	3	13	7.2	0.94	2.56		2.52		
C	7			990	3,700				7												
D	4		300		3,450	0.74	50	0.37	6	1, 90° 1, 60°	7	1, 30°	3	16	3.6 5.6	0.25 0.90	2.01		2.77 2.77		
			350		h_a difference about 20%; increase cfm to: $300\sqrt{\frac{2.77}{2.01}} = 350$																
E	8			1,340	3,800				3								2.77		2.77		
F	$5\frac{1}{2}$		600		3,600	0.81	50	0.40	11	2, 90° 1, 60°	15	1, 30°	4	30	3.4 4.4	0.10 1.32	2.53		2.87 2.87		
			640		h_a difference is between 5 and 20%; increase cfm to: $600\sqrt{\frac{2.87}{2.53}} = 640$																
G	10			1,980	3,600	0.81			12	2, 90°	22			34	2.6	0.88	2.87		2.87 3.75		
			Cloth filter dust collector resistance = 4 in.																		
H	10			1,980	3,600				8					8	2.6	0.21			7.75		

Fan static pressure = h_s inlet + h_s outlet - h_v inlet

= 7.75 + 0.21 - 0.81 = 7.15 in. WC

[a] In a duct on the inlet side of a fan, $h_s = O.L. + 1\ h_v + h_F$. On the outlet side, $h_s = h_F$. For fans rated under the NAFM-ASHVE and ASME codes, fan h_s = h_s inlet + h_s outlet - h_v inlet.

Table 14. EXHAUST SYSTEM CALCULATIONS BY THE BLAST-GATE METHOD

1	2	3	4		5	6	7		8	9		10		11	12	13	14			15
No. of branch or main	Duct diam, in.	Gas temp, °F	Volume, cfm		Velocity, fpm	One h_v at 70°F	Hood loss		Length straight duct, ft	Elbows		Branch entry		Total equivalent length, ft	Resistance per 100 ft	h_r in WC at 70°F	Static pressure[a]			Cor. br. vel.
			Branch	Main			% h_v	in. WC		No. and angle	Equivalent length, ft	Angle	Equivalent length, ft				Branch at 70°F	Branch at T°F	Main	
A	6		750		3,800	0.90	50	0.45	14	2, 90°	12			26	4.5	1.17	2.52			
B	$3\frac{1}{2}$		230		3,500	0.76	100	0.76	4	1, 90° 1, 60°	6	1, 30°	3	13	6.5	0.85	2.37	a	2.52	
C	7			980	3,700				7					7	3.7	0.26			2.78	
D	4		305		3,500	0.76	50	0.38	6	1, 90° 1, 60°	7	1, 30°	3	16	5.6	0.90	2.04	a	2.78	
E	8			1,285	3,650				3					3	3.0	0.09			2.87	
F	$5\frac{1}{2}$		600	1,885	3,600	0.81	50	0.40	11	2, 90° 1, 60°	15	1, 30°	4	30	4.5	1.35	2.56	a	2.87	
G	10			1,885	3,500	0.76			12	2, 90°	22			34	2.2	0.75			3.62	
							Cloth filter dust collector resistance = 4 in.												7.62	
H	10			1,885	3,500				8					8	2.2	0.18				

Fan static pressure = h_s inlet + h_s outlet - h_v inlet
= 7.62 + 0.18 - 0.76 = 7.04 in. WC

[a]Use highest h_s at junction of branches.

Table 15. CALCULATIONS FOR CHECKING AN EXHAUST SYSTEM

1	2	3	4	5	6		7	8		9		10	11	12	13			14	15		16
No. of branch or main	Duct diam, in.	Gas temp, °F	Velocity, fpm	One h_v at 70°F	Hood loss		Length straight duct, ft	Elbows		Branch entry		Total equivalent length, ft	Resistance per 100 ft	h_r in. WC at 70°F	Static pressure[a]			Corrected branch velocity, fpm	Volume, cfm		Temp in main, °F
					% h_v	in. WC		No. and angle	Equivalent length, ft	Angle	Equivalent length, ft				Branch at 70°F	Branch at T°F	Main		Branch	Main	
A-C	4	70°	3,500	0.76	65	0.50	22	2, 90°	8			30	5.5	1.65	2.91		2.91		320	320	
B-C	5		3,500	0.76	65	0.50	20	2, 90°	10	30°	4	34	4.4	1.50	2.76		2.91	3,600	480	800	
C-G	6		4,100				12					12	5.0	.60			3.51			800	
D-F	3		3,500	0.76	65	0.50	12	2, 90°	6			18	7.3	1.31	2.57			3,500	170		
E-F	4		3,500	0.76	65	0.50	16	2, 90° 1, 60°	8 3	30°	3	30	5.5	1.65	2.91			3,300	290		
F-G	5		3,400				14	1, 60°	4	30°	4	22	4.1	0.90	3.47		3.51	3,420	460	1,260	
G-I	8		3,600				12					12	2.9	0.35			3.86			1,260	
H-I	4		3,500	0.76	65	0.50	20	2, 90° 1, 60°	8 3	30°	3	34	5.5	1.87	3.13		3.86	3,900	340	1,600	
I-J	9		3,600	0.81			22	1, 90°	10			32	2.6	0.83			4.69			1,600	
Cyclone	12-in. x 6-in. entry		3,200	0.64	150	0.96											5.65			1,600	

Fan h_s = 5.65 - 0.81 = 4.84 in. WC

[a] In a duct on the inlet side of a fan, $h_s = O.L. + 1\ h_v + h_r$. On the outlet side, $h_s = h_r$. For fans rated under the NAFM-ASHVE and ASME codes, fan h_s = h_s inlet + h_s outlet - h_v inlet.

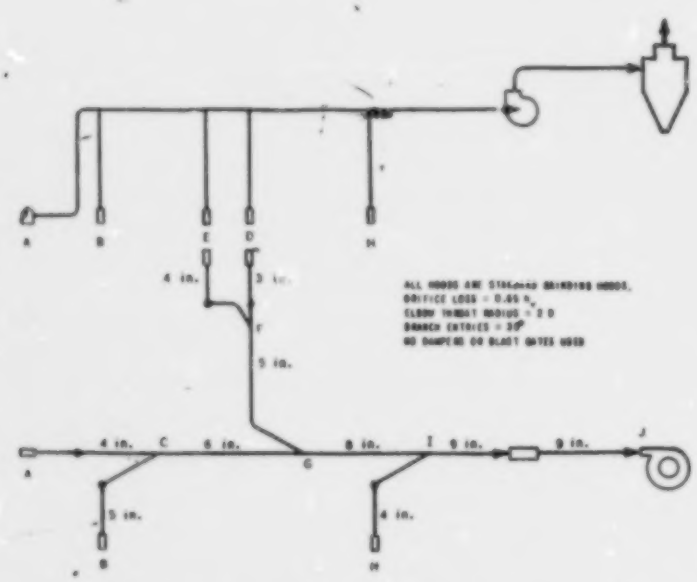


Figure 22. Layout of ductwork used in example showing procedure in checking an exhaust system

Since assumed values of volume are used in the calculations, the final result is the system's resistance at a given total volume. The system's resistance will increase with increase in volume by the square of the ratio of the increase in volume. On the other hand, the capacity of an exhauster decreases with increase in resistance. The one point that satisfies both system and fan can best be found by plotting the characteristic curves of the system and the fan. The operating point is the point of intersection of the two curves. The system's characteristic curve is that curve established by the static pressure losses through the exhaust system for various air volumes. It is computed by starting with the resistance and volume from Table 15 and calculating the resistance at other volumes by using the square of the ratio of the volume change. The curve for the sample problem is computed from Table 16.

Table 16. CALCULATIONS FOR CHARACTERISTIC CURVE

Volume, cfm	Multiplying factor	New h_s
1,600		4.84
1,800	$(1,800/1,600)^2 \times 4.84$	6.12
2,000	$(2,000/1,600)^2 \times 4.84$	7.56
1,400	$(1,400/1,600)^2 \times 4.84$	3.71
1,200	$(1,200/1,600)^2 \times 4.84$	2.72
1,000	$(1,000/1,600)^2 \times 4.84$	1.89
500	$(500/1,600)^2 \times 4.84$	0.47

Fan h_s is used in computing this curve because the fan, a Chicago No. 25 Steel Plate Exhauster, is rated by the methods of the National Association of Fan Manufacturers (NAFM). The fan characteristic curves are families of curves at different fan speeds defining static pressures developed for various volumes of air handled through the fan. These data are available from fan manufacturers. Data for the single fan curve at 2,600 rpm as specified by this example are obtained from Chicago Blower Corporation Bulletin SPE-102. Fan capacities at various static pressures and at the given speed nearest to 2,600 rpm are tabulated on the left in Table 17; on the right the figures are corrected to 2,600 rpm by use of the fan laws, as follows:

$$cfm_2 = cfm_1 \times \left[\frac{rpm_1}{rpm_2}\right]$$

$$h_{s_2} = h_{s_1} \times \left[\frac{rpm_1}{rpm_2}\right]^2$$

$$hp_2 = hp_1 \times \left[\frac{rpm_1}{rpm_2}\right]^3$$

A horsepower versus air volume curve can also be plotted from Table 17.

Table 17. FAN CAPACITY AT VARIOUS STATIC PRESSURES

From Chicago Bulletin				Corrected to 2,600 rpm		
rpm	cfm	h_s	hp	cfm	h_s	hp
2,630	2,470	5	4.44	2,440	4.9	4.3
2,615	2,240	$5\frac{1}{2}$	3.89	2,230	5.4	3.8
2,605	2,005	6	3.44	2,000	6.0	3.4
2,625	1,655	7	3.09	1,640	6.9	3.0
2,620	1,065	8	2.54	1,050	7.8	2.5

The system curve, fan curve, and horsepower curve are plotted in Figure 23. The fan and system curves intersect at 1,860 cfm and 6.5 inches h_s. The horsepower required is 3.2.

Since the volume obtained from the curves of Figure 23 is appreciably higher than the total volume from Table 15, the volume at each hood must be corrected. The correction factor is obtained by dividing the volume from the curve by the total volume from Table 15. Corrections are made in Table 18.

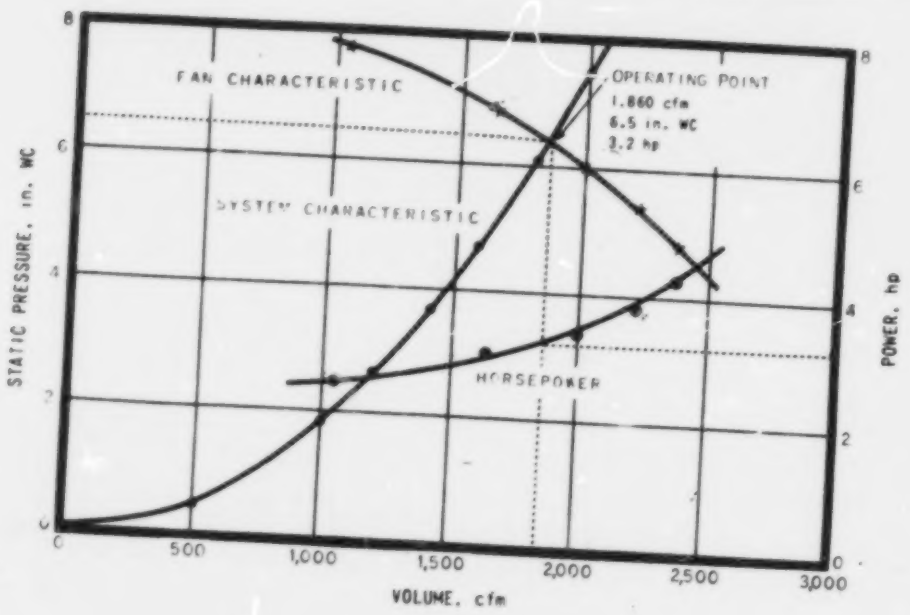


Figure 23. Characteristic curves of an exhaust system.

Fan Curve Calculator

The calculations required to produce a fan curve from catalog data have been incorporated in a slide rule-type calculator (Figure 24). A calculator of this type will reduce the time required to plot characteristic curves such as shown in Figure 23.

CORRECTIONS FOR TEMPERATURE AND ELEVATION

Fan tables, resistance charts, and exhaust volume requirements are based on standard atmospheric conditions of 70°F and average barometric pressure at sea level. Under these conditions the density of air is 0.075 pound per cubic foot. Where conditions vary appreciably from standard conditions, the change in air density must be considered.

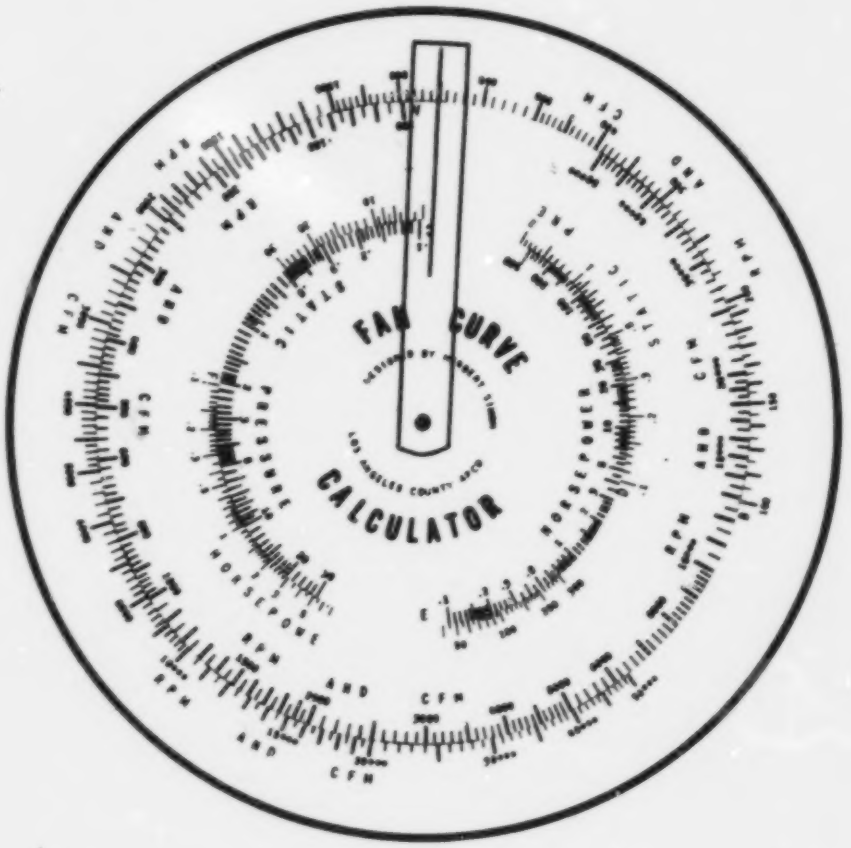


Figure 24. Fan curve calculator.

Table 18. CORRECTIONS FOR HOOD VOLUME

Hood	Volume from Table 15, cfm	Correction factor	Corrected volume, cfm
A	320	1,860/1,600	370
B	480	1,860/1,600	560
D	170	1,860/1,600	200
E	290	1,860/1,600	340
H	340	1,860/1,600	390

The density of air varies inversely with absolute temperature and directly with barometric pressure. Both effects are combined in the density correction factors given in Table 19.

Velocity pressure, static pressure, and resistance pressure vary directly with gas density. In calculating a system, if the temperatures in all the ducts are approximately the same (within 25°F), compute the entire system's resistance as at standard conditions and correct the final system's static pressure by multiplying by the density correction factor. If the temperatures in the different branches vary, the static pressure in each branch must be corrected.

A centrifugal fan connected to a given system will exhaust the same volume regardless of gas density. The weight of air exhausted will, however, be directly proportional to the density, and so will the static pressure developed and the horsepower consumed.

In selecting an exhauster from multirating tables to move a given volume of air at a given static pressure and at a given temperature and altitude, proceed as follows:

1. Read the density correction factor from Table 19.
2. Divide the given h_s by the correction factor.
3. Select the fan size and rpm based on the given volume and the corrected static pressure.
4. Multiply the horsepower (given by the above selection) by the density correction factor to obtain the required horsepower.

Table 19. DENSITY CORRECTION FACTORS[a]

	Altitude, ft above sea level								
Temp, °F	0	1,000	2,000	3,000	4,000	5,000	6,000	7,000	8,000
0	1.15	1.10	1.06	1.01	0.99	0.95	0.92	0.88	0.85
40	1.06	1.02	0.98	0.94	0.91	0.88	0.84	0.81	0.79
70	1.00	0.96	0.93	0.89	0.86	0.83	0.80	0.78	0.74
100	0.96	0.91	0.88	0.84	0.81	0.78	0.75	0.72	0.70
120	0.92	0.88	0.85	0.81	0.78	0.75	0.72	0.70	0.67
140	0.88	0.85	0.82	0.79	0.76	0.73	0.70	0.68	0.65
160	0.85	0.82	0.79	0.76	0.74	0.70	0.68	0.65	0.63
180	0.83	0.79	0.77	0.74	0.71	0.68	0.66	0.63	0.61
200	0.80	0.77	0.74	0.71	0.68	0.66	0.64	0.61	0.59
250	0.75	0.72	0.70	0.67	0.64	0.62	0.60	0.58	0.55
300	0.70	0.67	0.65	0.62	0.60	0.58	0.56	0.54	0.52
350	0.65	0.62	0.60	0.58	0.56	0.54	0.52	0.50	0.48
400	0.62	0.60	0.57	0.55	0.53	0.51	0.49	0.47	0.44
450	0.58	0.56	0.54	0.52	0.50	0.48	0.46	0.44	0.42
500	0.55	0.53	0.51	0.49	0.47	0.45	0.44	0.42	0.40
550	0.53	0.51	0.49	0.47	0.45	0.44	0.42	0.40	0.38
600	0.50	0.48	0.46	0.45	0.43	0.41	0.40	0.38	0.36
650	0.48	0.46	0.44	0.43	0.41	0.40	0.38	0.36	0.34
700	0.46	0.44	0.43	0.41	0.39	0.38	0.37	0.35	0.33
750	0.44	0.42	0.41	0.39	0.38	0.36	0.35	0.33	0.32
800	0.42	0.40	0.39	0.37	0.36	0.35	0.33	0.32	0.31
850	0.40	0.38	0.37	0.36	0.34	0.33	0.32	0.31	0.30
900	0.39	0.37	0.36	0.35	0.33	0.32	0.31	0.30	0.29
950	0.38	0.36	0.35	0.34	0.32	0.31	0.30	0.29	0.28
1,000	0.36	0.35	0.33	0.32	0.31	0.30	0.29	0.28	0.27

[a]Density in lb/ft^3 = 0.075 x density factor.

The procedure for plotting the fan's characteristic curve at other than standard conditions is as follows:

1. Correct the values of cfm, h_s, and hp from the tables to the given rpm.

2. Multiply the values of h_s and hp by the density correction factor.

3. Plot values of h_s and hp from Step 2 against values of cfm from Step 1.

DUCT CONSTRUCTION

Correct design and competent installation of sheet steel ducts and hoods are necessary for the proper functioning of an exhaust system. The following construction and installation practices are recommended (Industrial Ventilation, 1956):

1. All exhaust systems should be constructed of new materials and installed in a permanent and workmanlike manner. Interior of all ducts should be smooth and free from obstructions, with joints either welded or soldered airtight.

2. Ducts should be constructed of galvanized sheet steel riveted and soldered or black iron welded, except where corrosive gases or mists or other factors make such materials impractical. Galvanized construction is not recommended for temperatures above 400°F. Welding of black iron of 18 gauge and lighter is not recommended for field fabrication.

3. For average exhaust on noncorrosive application, the following gauges should be used for straight duct:

Duct diameter	U. S. Standard gage		
	Class I	Class II	Class III
To 8 in.	24	22	20
$8\frac{1}{2}$ to 18 in.	22	20	18
19 to 30 in.	20	18	16
Over 30 in.	18	16	14

Class I. Includes nonabrasive applications, such as paint spraying, woodworking, food products, and discharge ducts from dust collectors.

Class II. Includes nonabrasive material in large concentration, moderately abrasive material in small to moderate concentrations, and highly abrasive material in small concentration.

Class III. Includes all highly abrasive material in moderate to heavy concentrations and moderately abrasive material in heavy concentration.

Brown and Sharpe gage numbers are used to indicate thickness of aluminum sheet as compared with U. S. Standard gages for steel sheet. When aluminum is indicated, the following equivalent B and S gages should be used:

Steel - U. S. Standard gage
26 24 22 20 18 16 14

Aluminum - B and S gage
24 22 20 18 16 14 12

4. Elbows and angles should be a minimum of two gauges heavier than straight sections of the same diameter.

5. Longitudinal joints of the ducts should be lapped and riveted or spot-welded on 3-inch centers or less.

6. Girth joints of ducts should be made with the lap in the direction of airflow. A 1-inch lap should be used for ducts to 19-inch diameters and 1-1/4-inch laps for diameters over 19 inches.

7. All bends should have an inside or throat radius of two pipe diameters whenever possible, but never less than one diameter. Large radii bends are recommended for heavy concentrations of highly abrasive dust. Ninety degree elbows not over 6 inches in diameter should be constructed of at least five sections, and over 6-inch diameter of at least seven sections.

8. The duct should be connected to the fan inlet by means of a split-sleeve drawband at least one pipe diameter long, but not less than 5 inches.

9. Transition in main and submains should be tapered, with a taper of about 5 inches for each 1-inch change in diameter.

10. All branches should enter main at the large end of transition at an angle not to exceed 45°, preferably 30° or less. Branches should be connected only to the top or sides of main, never to the bottom. Two branches should never enter a main at diametrically opposite points.

11. Dead-end caps should be provided on mains and submains about 6 inches from the last branch.

12. Cleanout openings should be provided every 10 or 12 feet and near each bend or duct junction.

13. The ducts should be supported sufficiently so that no load is ever placed on connecting equipment. Ducts 8 inches or smaller should be supported at least every 12 feet, and larger ducts, at least every 20 feet.

14. A minimum clearance of 6 inches should be provided between the ducts and ceilings, walls, or floors.

15. Blast gates used for adjusting a system should be placed near the connection of branch to main, and means provided for locking them in place after the system has been balanced.

16. Round ducts should be used wherever possible. Where clearances prevent the use of round ducts, rectangular ducts as nearly square as possible may be used.

FAN DESIGN

Fans are used to move air from one point to another. In the control of air pollution, the fan, blower, or exhauster imparts movement to an air mass and conveys the air contaminants from the source of generation to a control device in which the air contaminants are separated and collected, allowing cleaned air to be exhausted to the atmosphere.

Fans are divided into two main classifications: (1) radial-flow or centrifugal type, in which the airflow is at right angles to the axis of rotation of the rotor, and (2) axial-flow or propeller type, in which the airflow is parallel to the axis of rotation of the rotor.

CENTRIFUGAL FANS

A centrifugal fan consists of a wheel or rotor mounted on a shaft that rotates in a scroll-shaped housing. Air enters at the eye of the rotor, makes a right-angle turn, and is forced through the blades of the rotor by centrifugal force into the scroll-shaped housing. The centrifugal force imparts static pressure to the air. The diverging shape of the scroll also converts a portion of the velocity pressure into static pressure.

Centrifugal fans may be divided into three main classifications as follows:

1. Forward-curved-blade type. The rotor of the forward-curved-blade fan is known as the squirrel-cage rotor. A solid steel backplate holds one end of the blade, and a shroud ring supports the other end. The blades are shallow with the leading edge curved towards the direction of rotation. The usual number of blades is 20 to 64.

2. Backward-curved-blade type. In the backward-curved-blade fan, the blades are inclined in a direction opposite to the direction of rotation, and the blades are larger than those of the forward-curved-blade fan. The usual number of blades is 14 to 24, and they are supported by a solid steel backplate and shroud ring.

3. Straight-blade type. The blades of the straight-blade fan may be attached to the rotor by a solid steel backplate or a spider built up from the hub. The rotors are of comparatively large diameter. The usual number of blades is 5 to 12. This classification includes a number of modified designs whose characteristics are, in part, similar to those of the forward- and backward-curved blade types.

AXIAL-FLOW FANS

Axial-flow fans include all those wherein the air flows through the impellers substantially parallel with the shaft upon which the impeller is mounted. Axial-flow fans depend upon the action of the revolving airfoil-type blades to pull the air in by the leading edge and discharge it from the trailing edge in a helical pattern of flow. Stationary vanes may be installed on the suction side or the discharge side of the rotor, or both. These vanes convert the centrifugal force and the helical-flow pattern to static pressure.

Axial fans may be divided into three main classifications:

1. Propeller type. Propeller fans have large, disc-like blades or narrow, airfoil-type blades. The number of blades is 2 to 16. The propeller fan blades may be mounted on a large or small hub, depending upon the use of the fan. The propeller fan is distinguished from the tube-axial and vane-axial fans in that it is equipped with a mounting ring only.

2. Tube-axial type. The tube-axial fan is similar to the propeller fan except it is mounted in a tube or cylinder. It is more efficient than the propeller fan and, depending upon the design of the rotor and hub, may develop medium pressures. A two-stage, tube-axial fan, with one rotor revolving clockwise and the second, counter-clockwise, will recover a large portion of the centrifugal force as static pressure, which would otherwise be lost in turbulence. Two-stage, tube-axial fans approach vane-axial fans in efficiency.

3. Vane-axial type. The vane-axial fan is similar in design to a tube-axial fan except that air-straightening vanes are installed on the

suction side or discharge side of the rotor. Vane-axial fans are readily adaptable to multistaging, and fans have been designed that will operate at a pressure of 16 inches water column at high volume and efficiency.

FAN CHARACTERISTICS

The performance of a fan is characterized by the volume of gas flow, the pressure at which this flow is produced, the speed of rotation, the power required, and the efficiency. The relationships of these quantities are measured by the fan manufacturer with testing methods sponsored by the National Association of Fan Manufacturers or the American Society of Mechanical Engineers. Briefly, the method consists of mounting a duct on the fan outlet, operating the fan with various sized orifices in the duct, and measuring the volume, pressure, velocity, and power input. About 10 tests are run, with the duct opening varied from wide open to completely closed. The test results are then plotted against volume on the abscissa to provide the characteristic curves of the fan, such as those shown in Figure 25.

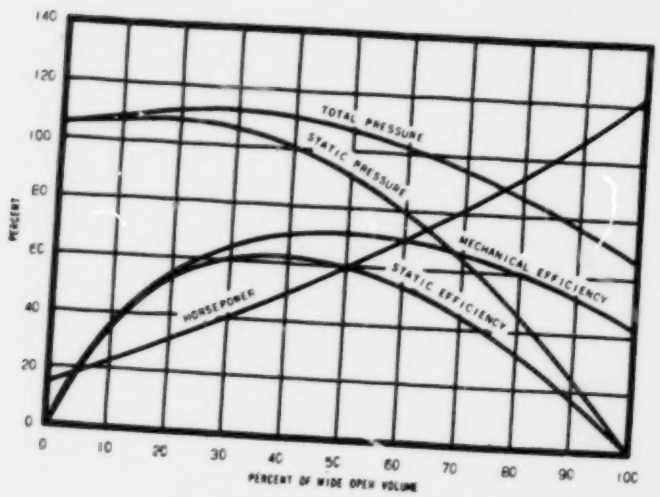
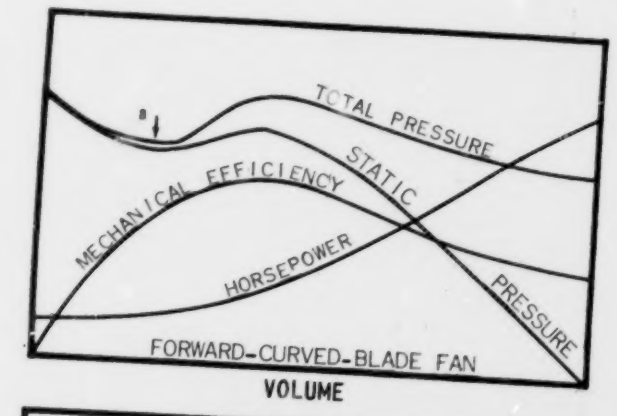


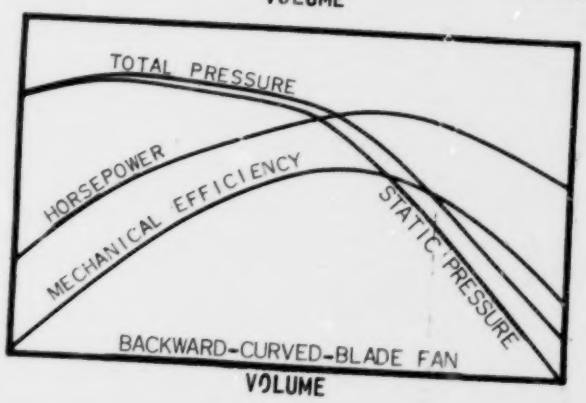
Figure 25. Typical fan characteristic curves (Air Moving and Conditioning Assn., Inc., 1963).

From the volume and pressure, the air horsepower is computed, either the real power based on total pressure or the fictitious static power based on fan static pressure. The efficiency based on total pressure is called mechanical efficiency.

INFLUENCE OF BLADE SHAPE

The size, shape, and number of blades in a centrifugal fan have a considerable influence on the operating characteristics of the fan. The general effects are indicated by the curves in Figure 26.





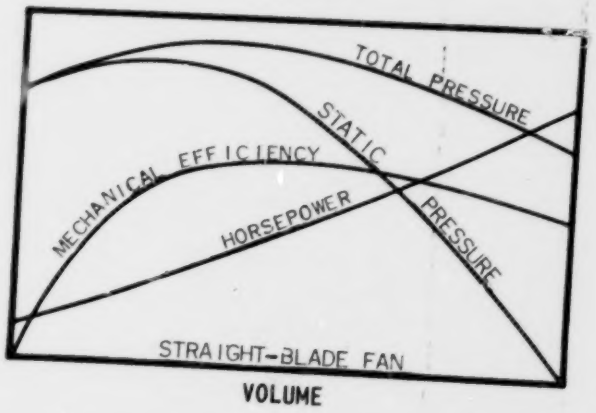


Figure 26. Centrifugal fan typical characteristic curves (Hicks, 1951).

These curves are shown for comparison purposes only; they are not applicable for fan selection but do indicate variations in the operating characteristics of a specific type of fan.

1. Forward-Curved-Blade Fans. This type of fan is normally referred to as a volume fan. In this fan, the static pressure rises sharply from free delivery to a point at approximate maximum efficiency, then drops to point a shown in Figure 26, before rising to static pressure at no delivery. Horsepower input rises rapidly from no delivery to free delivery. Sound level is least at maximum efficiency and greatest at free delivery. Forward-curved-blade fans are designed to handle large volumes of air at low pressures. They rotate at relatively low speeds, which results in quiet operation. Initial cost of such a fan is low.

Resistance of a system to be served by this type of fan must be constant and must be determined accurately in advance because of sharply rising power demand. This type of fan should not be used for gases containing dusts or fumes because deposits will accumulate on the short curved blades resulting in an unbalanced wheel and excessive maintenance. The pressure produced by a forward-curved-blade fan is not normally sufficient to meet the pressure requirements for the majority of air pollution control devices. They are, however, used extensively in heating, ventilating, and air conditioning work. Also, they are commonly used for exhausting air from one enclosed space to another without the use of ductwork.

2. Backward-Curved-Blade Fans. The static pressure of this type fan rises sharply from free delivery almost to the point of no delivery. Maximum efficiencies occur at maximum horsepower input. The horsepower requirement is self-limiting; it rises to a maximum as the capacity increases and then decreases with additional capacity. Thus, when the resistance of a complex exhaust system is frequently changed because of production demands, the self-limiting power requirements prevent overloading the motor.

This type of fan develops higher pressure than the forward-curved-blade type. Sound level is least at maximum efficiency and increases slightly at free delivery. The physical sizes of backward-curved-blade fans for given duties are large, but for most industrial work this may be unimportant. The operating efficiency is high, but initial cost is also high. Blade shape is conducive to buildup of material and should not be used on gases containing dusts or fumes.

The backward-curved-multiblade fan is used extensively in heating, ventilating, and air conditioning work and for continuous service where a large volume of air is to be handled. It is commonly found on forced-draft combustion processes. It may be used on some air pollution control devices, but must be installed on the clean air discharge as an induced system.

3. Straight-Blade Fans. The static pressure of this type fan rises sharply from free delivery to a maximum point near no delivery, where it falls off. Maximum static efficiency occurs near maximum pressure. Mechanical efficiency rises rapidly from no delivery to a maximum near maximum pressure, then drops slowly as the fan capacity approaches free delivery.

This type fan is utilized for exhaust systems handling gas streams that are contaminated with dusts and fumes. Various blades and scroll designs have been developed for specific dust-handling and pneumatic-conveying problems. This fan is too large for some duties, but for most industrial work this may be unimportant. Initial cost of this type fan is less than that of the backward-curved-blade type, but efficiency is also less. Fan blades may be made of an abrasive resistant alloy or covered with rubber to prevent high maintenance in systems handling abrasive or corrosive materials.

A number of modified designs of straight-blade fans have been specifically developed for handling contaminated air or gas streams.

4. Axial Fans. For this type fan, the horsepower curve may be essentially flat and self-limiting, depending upon the design of the blades, or it may fall from a maximum at no delivery as capacity increases. The type of vanes in the vane-axial fans measurably affects the horsepower curve and efficiency. Maximum efficiencies occur at a higher percent delivery than with the centrifugal-type fan.

Space requirements for a specific fan duty are exceptionally low. Available fans can be installed directly in circular ducts (vane-axial or tube-axial type). Initial cost of the fan is low.

The axial-type fan is best adapted for handling large volumes of air against low resistance. The propeller type, which is equipped only with a mounting ring, is commonly used for ventilation and is mounted directly in a wall. Although the vane-axial and tube-axial fans can deliver large volumes of air at relatively high resistances, they are best suited for handling clean air only. Any solid material in the air being handled causes rapid erosion of impellers, guide vanes, hubs, and the inner wall of the cylindrical fan housing. This results from the high tip speed of the fan and the high air velocity through the fan housing.

Geometrically Similar Fans

Fan manufacturers customarily produce a series of fans characterized by constant ratios of linear dimensions and constant angles between various fan parts. These fans are said to be geometrically similar or of a homologous series. The drawings of all the fans in the series are identical in all views except for scale.

It is usual for a manufacturer to produce homologous series of fans with diameters increasing by a factor of about 1.10. Each is designated by the impeller diameter or by an arbitrary symbol, often a number proportional to the diameter.

Multirating Tables

The performance of each fan in a homologous series is usually given in a series of tables called multirating tables. Values of static pressure are usually arranged as headings of columns, which contain the fan speed and horsepower required to produce various volume flows. The point of maximum efficiency at each static pressure is usually indicated.

FAN LAWS

Certain relationships have been established among the variables affecting the performance of fans of a homologous series or a single fan operating at varying speed in a constant system. The quantity, V_t, and the power, p, are controlled by four independent variables: (1) Fan size, wheel diameter, D, (2) fan speed, N, (3) gas density, ρ, and (4) system resistance, h_r. Since all dimensions of homologous fans are proportional, any dimension could be used to designate the size. The wheel diameter is, however, nearly always used.

In order to develop these relationships, the effects of system resistance must be fixed by limiting the comparisons to the same points of rating. For two fans of different size, the same point of rating is obtained when the respective volumes are the same percentage of wide open volume, and the static pressure is the same percentage of shut-off static pressure. For the same fan, the same point of rating is obtained when the system is held constant and the fan speed is varied.

For homologous fans (or the same fan) operating at the same point of rating, the quantity (V_t) and the power (P) will depend upon the fan size (D), fan speed (N), and gas density (ρ). The flow through a fan is always in the turbulent region, and the effect of viscosity is ignored. The form of dependence can be derived from dimensional analysis by the equation

$$V_t = k D^a N^b \rho^c \qquad (27)$$

By substituting fundamental dimensional units,

$$L^3 t^{-1} = L^a \left[t^{-1}\right]^b \left[mL^{-3}\right]^c$$

equating exponents for like terms,

$$m: \ 0 = c$$

$$L: \ 3 = a - 3c$$

$$t: -1 = -b$$

and solving the equations simultaneously

$$a = 3; \quad b = 1; \quad c = 0$$

hence:

$$V_t = k D^3 N \qquad (28)$$

Repeating for the system resistance developed and noting that h_r is fundamentally force per unit area = mass × acceleration per area,

$$h_r = kD^a N^b \rho^c$$

$$mL^{-1}t^{-2} = L^a \left[t^{-1}\right]^b \left[mL^{-3}\right]^c$$

$$m \quad 1 = c$$

$$L \quad -1 = a - 3c$$

$$t \quad -2 = -b$$

$$a = 2; \quad b = 2; \quad c = 1$$

$$h_r = kD^2 N^2 \rho \qquad (29)$$

And repeating again for the power required:

$$P = kD^a N^b \rho^c$$

$$mL^2 t^{-3} = k L^a \left[t^{-1}\right]^b \left[mL^{-3}\right]^c$$

$$m \quad 1 = c$$

$$L \quad 2 = a - 3c$$

$$t \quad -3 = -b$$

$$a = 5; \quad b = 3; \quad c = 1$$

$$P = kD^5 N^3 \rho \qquad (30)$$

Equations 28, 29, and 30 for V_t, h_r, and P define the relationships among all the variables, within the limitations originally stated. The equations can be simplified, combined, or modified to yield

a large number of relationships. The following relationships derived from them are usually referred to as the Fan Laws.

1. Change in Fan Speed.

   Fan size, gas density, and system constant.

   a. V_t varies as fan speed.

   b. h_r varies as fan speed squared.

   c. P varies as fan speed cubed.

2. Change in Fan Size.

   Fan speed and gas density constant.

   a. V_t varies as cube of wheel diameter.

   b. h_r varies as square of wheel diameter.

   c. P varies as fifth power of wheel diameter.

   d. Tip speed varies as wheel diameter.

3. Change in Fan Size.

   Tip speed and gas density constant.

   a. V_t varies as square of wheel diameter.

   b. h_r remains constant.

   c. P varies as square of wheel diameter.

   d. rpm varies inversely as wheel diameter.

4. Change in Gas Density.

   System, fan speed, and fan size constant.

   a. V_t is constant.

   b. h_r varies as density.

   c. P varies as density.

5. Change in Gas Density.

   Constant pressure and system, fixed fan size, and variable fan speed.

   a. V_t varies inversely as square root of density.

   b. Fan speed varies inversely as square root of density.

   c. P varies inversely as square root of density.

6. Change in Gas Density.

   Constant weight of gas, constant system, fixed fan size, and variable fan speed.

   a. V_t varies inversely as gas density.

   b. h_r varies inversely as gas density.

   c. Fan speed varies inversely as gas density.

   d. P varies inversely as square gas density.

The fan laws enable a manufacturer to calculate the operating characteristics for all the fans in a homologous series from test data obtained from a single fan in the series. The laws also enable users of fans to make many needed computations. A few of the more important cases are illustrated as follows.

Example 11

A fan operating at 830 rpm delivers 8,000 cfm at 6 inches static pressure and requires 11.5 horsepower. It is desired to increase the output to 10,000 cfm in the same system. What should be the increased speed and what will be the horsepower required and the new static pressure?

Solution:

Use fan law 1 a , b , c :

$$N' = 830 \left[\frac{10,000}{8,000}\right] = 1,037 \text{ rpm}$$

$$h'_r = \gamma \left[\frac{1,037}{830}\right]^2 = 9.35 \text{ in. WC}$$

$$P' = 11.5 \left[\frac{1,037}{830}\right]^3 = 22.4 \text{ hp}$$

Example 12

A fan is exhausting 12,000 cfm of air at 600°F. (density = 0.0375 pound per cubic foot at 4 inches static pressure from a drier). Speed is 630 rpm, and 13 horsepower is required. What will be the required horsepower if air at 70°F (density 0.075 pound per cubic foot) is pulled through the system?

Solution:

Use fan law 4 c :

$$P' = 13 \left[\frac{0.075}{0.375}\right] = 26 \text{ hp}$$

If a 15-horsepower motor were used in this installation, it would be necessary to use a damper when starting up cold to prevent overloading the fan motor.

Example 13

A 30-inch-diameter fan operating at 1,050 rpm delivers 4,600 cfm at 5 inches static pressure. What size fan of the same series would deliver 11,000 cfm at the same static pressure?

Solution:

Use fan law 2 a .

$$D' = \left(\frac{11,000}{4,600}\right)^{1/3} (30) = 40.0 \text{ in.}$$

Selecting a Fan From Multirating Tables

A typical multirating table is given in Table 20. The data in this table are for a paddle wheel-type industrial exhauster. In using multirating tables, use linear interpolation to find values between those given in the table. For instance, from Table 20 it is desired to find the fan speed that will deliver 6,300 cfm at 6-1/2 inches static pressure. The nearest capacities are 6,040 and 6,550.

At 6 in. h_s the speed is

$$1,088 + \frac{6,300-6,040}{6,550-6,040} (1,095 - 1,088) = 1,092 \text{ rpm.}$$

At 7 in. h_s the speed is

$$1,160 + \frac{6,300-6,040}{6,550-6,040} (1,171 - 1,160) = 1,167 \text{ rpm.}$$

The required speed at 6-1/2 inches static pressure and 6,300 cfm is halfway between 1,092 and 1,167 or 1,129 rpm.

CONSTRUCTION PROPERTIES

Special materials of construction must be used for fans handling corrosive gases. Certain alloys that have been used have proved very satisfactory. Bronze alloys are used for handling sulfuric acid fumes and other sulfates, halogen acids, various organic gases, and mercury compounds. These alloys are particularly applicable to low-temperature installations. Stainless steel is the most commonly used metal for corrosion-resistant impellers and fan housings. It has proved satisfactory for exhausting the fumes of many acids. Protective coatings on standard fan housing and impellers such as bisonite, cadmium plating, hot galvanizing, and rubber covering have proved satisfactory. Cadmium plating and hot galvanizing are often used in conjunction with a zinc chromate primer, with which they form a chemical bond. The zinc chromate primer may then be covered with various types of paints. This combination has proved favorable in atmospheres near the ocean.

The increasing use of rubber for coating fan impellers and housings deserves special mention. Rubber is one of the least porous materials and, when vulcanized to the metal, surrounds and protects the metal from corrosive gases or fumes. Depending upon the particular application, soft, medium, or firm rubber is bonded to the metal. A good bond will yield an adhesive strength of 700 pounds per square inch. When pure, live rubber is so bonded, it is capable of withstanding the high stresses set up in the fan and is sufficiently flexible to resist cracking. Rubber-covered fans have proved exceptionally durable and are found throughout the chemical industry.

Heat Resistance

Standard construction fans with ball bearings can withstand temperatures up to 250°F. Water-cooled bearings, shaft coolers, and heat gaps permit operation up to 800°F. A shaft cooler is a separate, small, centrifugal fan that is mounted between the fan housing and the inner bearing and that circulates cool air over the bearing and shaft. A heat gap, which is merely a space of 1-1/2 to 2 inches between the bearing pedestal and fan housing, reduces heat transfer to the bearings by conduction.

Certain types of stainless steel will withstand the high temperatures encountered in the induced-draft fan from furnaces or combustion processes. Stainless steel fans have been known to withstand temperatures as high as 1,100°F without excess warping.

Explosive-Proof Fans and Motors

When an exhaust system is handling an explosive mixture of air and gas or powder, a material to be used in the construction of the fan must generally be specified to be one that will not produce a spark if accidentally struck by another metal. Normally, the fan impeller and housing are constructed of bronze or aluminum alloys, which precludes spark formation. Aluminum is frequently used on some of the narrower or smaller fans, especially those overhung on the motor shaft. Aluminum reduces the weight and vibration of the motor shaft and protects the motor bearing from excessive wear.

Table 20. TYPICAL FAN MULTIRATING TABLE (New York Blower Company, 1948)

Volume, cfm	Outlet velocity, fpm	Velocity pressure, in. WC	1 in. SP		2 in. SP		3 in. SP		4 in. SP		5 in. SP		6 in. SP		7 in. SP		8 in. SP		9 in. SP	
			rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp	rpm	bhp
2,520	1,000	0.063	437	0.63	595	1.27	728	2.00	837	2.66										
3,120	1,200	0.090	459	0.85	610	1.55	735	2.30	842	3.10										
3,530	1,400	0.122	483	1.05	626	1.87	746	2.72	847	3.57	943	4.60								
4,030	1,600	0.160	513	1.33	642	2.18	759	3.17	858	4.12	950	5.21	1,030	6.29						
4,530	1,800	0.202	532	1.61	666	2.56	774	3.63	876	4.63	964	5.82	1,040	6.92	1,125	8.18				
5,040	2,000	0.250	572	2.00	688	2.97	797	4.12	890	5.30	976	6.50	1,052	7.75	1,134	8.96	1,208	10.15	1,270	11.67
5,540	2,200	0.302	603	2.36	712	3.43	816	4.66	910	5.93	999	7.38	1,068	8.60	1,145	9.93	1,210	11.18	1,279	12.82
6,040	2,400	0.360	637	2.79	746	3.99	840	5.33	926	6.73	1,017	8.17	1,088	9.50	1,160	10.88	1,230	12.25	1,288	13.92
6,550	2,600	0.422	670	3.27	762	4.62	866	6.05	954	7.83	1,032	9.08	1,095	10.50	1,171	11.98	1,245	13.50	1,298	15.10
7,060	2,800	0.489	708	3.81	795	5.32	892	6.72	963	8.78	1,050	9.97	1,125	11.60	1,188	13.06	1,257	14.70	1,310	16.48
7,560	3,000	0.560	746	4.42	833	6.05	920	7.70	993	9.32	1,068	11.00	1,142	12.75	1,210	14.28	1,277	15.98	1,328	17.80
8,060	3,200	0.638			866	6.96	943	8.71	1,020	10.40	1,097	12.10	1,168	14.02	1,228	15.50	1,292	17.36	1,340	19.15
8,560	3,400	0.721			900	7.93	964	9.80	1,053	11.48	1,120	13.30	1,188	15.35	1,248	16.93	1,310	19.00	1,360	20.90
9,070	3,600	0.808					1,010	11.00	1,078	12.70	1,148	14.65	1,213	16.70	1,270	18.42	1,335	20.75	1,380	22.60
9,570	3,800	0.900					1,038	12.25	1,108	14.15	1,170	14.90	1,240	18.80	1,292	19.46	1,355	22.35	1,405	24.40
10,080	4,000	0.998					1,162	13.60	1,138	15.40	1,200	17.35	1,270	19.70	1,320	21.70	1,380	23.15	1,430	26.40
10,580	4,200	1.100							1,168	16.90	1,230	19.05	1,283	21.50	1,348	23.50	1,405	26.10	1,450	28.45
11,100	4,400	1.210							1,198	18.58	1,258	20.55	1,322	22.50	1,373	25.40	1,430	27.95	1,478	30.60
11,600	4,600	1.310							1,232	20.30	1,290	22.50	1,355	23.80	1,405	27.40	1,450	30.15	1,500	32.90
12,100	4,800	1.450							1,270	21.00	1,321	24.40	1,383	25.65	1,432	29.60	1,482	32.40	1,528	35.20
12,600	5,000	1.570							1,301	24.20	1,355	26.40	1,410	28.80	1,462	31.80	1,513	34.60	1,555	37.80
15,120	6,000	2.230													1,622	45.90	1,670	49.00	1,702	51.50

Explosive-proof motors and fan wheels are required by law for installation in places where an explosive mixture may be encountered. Exhaust systems such as those used in paint spray booths usually consist of an aluminum or bronze tube-axial fan and an explosive-proof motor that drives the fan wheel by indirect drive.

Fan Drives

All types of fans may be obtained with either direct drive or belt drive. Directly driven exhausters offer the advantage of a more compact assembly and ensure constant fan speed. They are not troubled by the belt slippage that occurs when belt-driven fan drives are not properly maintained. Fan speeds are, however, limited to the available motor speeds, which results in inflexibility except in direct-current application. A quick change in fan speed, which is possible with belt-driven fans, is a definite advantage in many applications.

VAPOR COMPRESSORS

Compressors are widely used in industry to increase the pressure of gases or vapors for a variety of reasons. They are used:

1. To provide the desired pressure for chemical and physical reactions;
2. to control boiling points of fluids, as in gas separation, refrigeration, and evaporation;
3. to evacuate enclosed volumes;
4. to transport gases or vapors;
5. to store compressible fluids as gases or liquids under pressure and assist in recovering them from storage or tank cars;
6. to convert mechanical energy to fluid energy for operating instruments, air agitation, fluidization, solid transport, blowcases, air tools, and motors.

Compressors normally take suction near atmospheric pressure and deliver fluids at pressures ranging upward to 40,000 psig in commercial applications and even higher in experimental uses. The capacity of commerically available compressors ranges from low volumes up to 3 million cfm.

TYPES OF COMPRESSORS

Vapors or gases can be compressed by either positive displacement or dynamic action. The positive-displacement compressors produce pressure by physically reducing the gas volume. The dynamic compressors increase pressure by accelerating the gas and converting the velocity into pressure in a receiving chamber. Positive-displacement compressors are of reciprocating- or rotary-displacement types. The dynamic compressors are centrifugal- or axial-flow machines. Figure 27 shows general compressor applications, and Table 21 gives general limits of compressors.

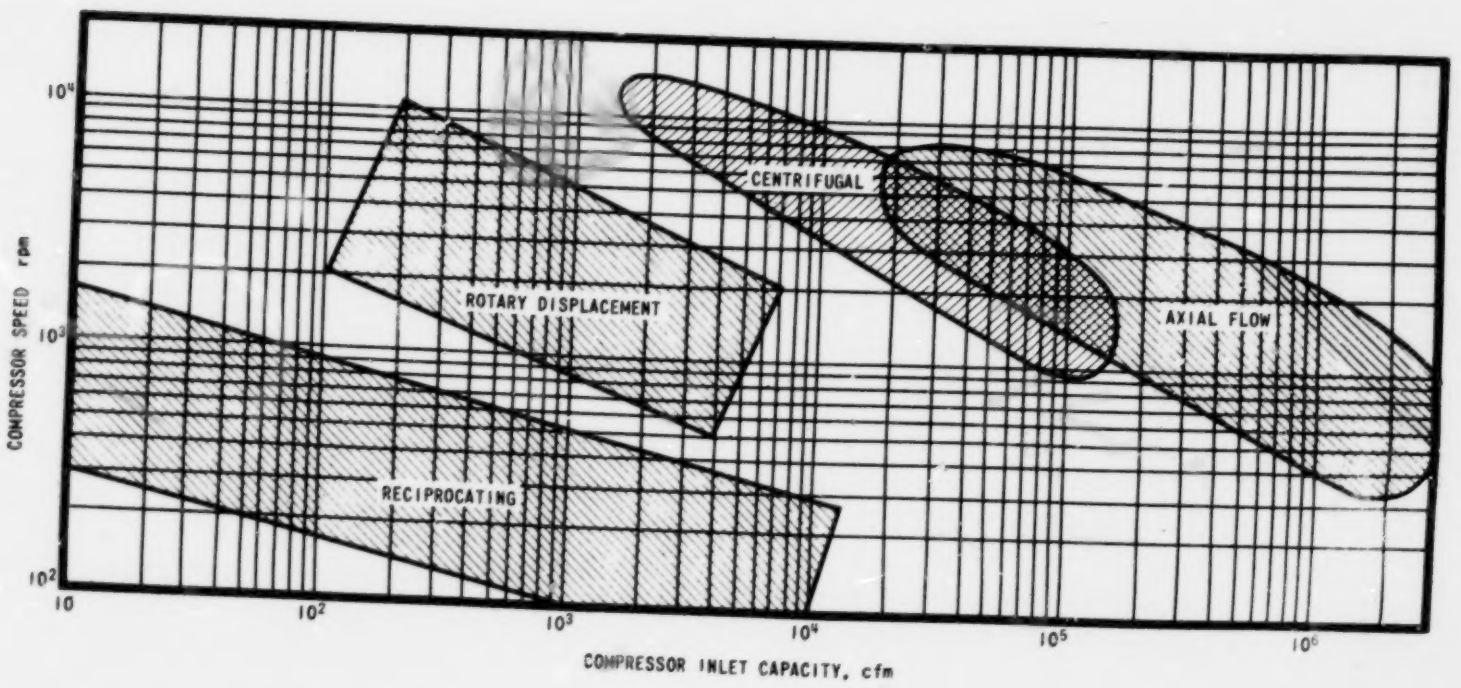


Figure 27. General areas of compressor applications (Des Jardins, 1956).

Table 21. GENERAL LIMITS OF COMPRESSORS
(Des Jardins, 1956)

Compressor type	Approximate maximum limits of commercially available compressors		
	Discharge pressure, psia	Compression ratio per stage	Inlet capacity, cfm
Reciprocating	35,000	10	13,000
Centrifugal	4,200	4	18,000
Rotary displacement	125	4	7,000
Axial flow	90	1.2	3,000,000

Positive-Displacement Compressors

A reciprocating compressor raises the pressure of the air or gas by the forced reduction of its volume through the movement of a piston within the confines of a cylinder. These compressors are commercially designed for volumes up to 15,000 cfm and pressures up to 40,000 psig. They are by far the most common type in use both for process systems and air pollution control systems (Cumiskey, 1956).

Rotary sliding-vane compressors have longitudinal vanes that slide radially in a rotor mounted eccentrically in a cylinder. The rotor is supported at each end by antifriction bearings mounted in the heads, which, in turn, are bolted and doweled to the cylinder. Figure 28 shows a cross-sectional view of a sliding-vane compressor.

In a sliding-vane unit, pressure is increased by reducing the size of the compression cell while it rotates from the suction to the discharge ports.

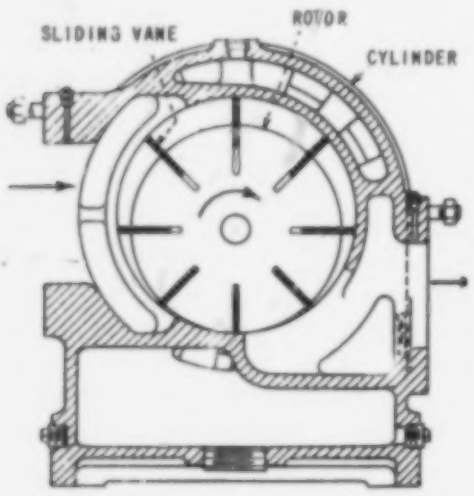


Figure 28. Sliding-vane compressor (Bruce and Schubert, 1956).

As the unit rotates, each compression cell reaches maximum size when it passes the inlet ports. Further rotation of this cell reduces its size, and compression is completed upon reaching the discharge ports (Bruce and Schubert, 1956). In general, single-stage, rotary, sliding-vane compressors are suitable for pressures up to 50 psig. Multistaged machines are designed for pressures up to 250 psig, and booster units are available for pressure up to 400 psig. These machines can deliver up to 6,000 cfm.

Rotary-lobe compressors have two mating, lobed impellers that revolve within a cylinder. Timing gears, mounted outside the cylinder, prevent the impellers from contacting each other. The lobes are mounted on shafts supported by antifriction bearings. Figure 29 shows a cross-sectional view of a rotary-lobe compressor. Flow through the rotary-lobe compressor is accomplished by the lobes' pushing the air or gas from the suction to the discharge. Essentially, no compression takes place within the unit; rather, compression takes place against system back pressure (Bruce and Schubert, 1956). Rotary-lobe compressors are available in sizes up to 50,000 cfm and pressures up to 30 psig. Single-stage machines are usually good for pressures up to 15 psig, and vacuums to 22 inches of mercury.

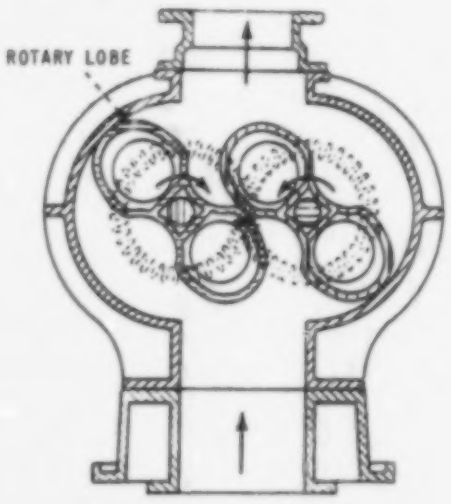


Figure 29. Rotary-lobe compressor, (Bruce and Schubert, 1956).

Rotary liquid-piston compressors use water or other liquids, usually in a single rotating element to displace the air or gas being handled. A rotating element is mounted on a shaft and supported at each end by antifriction bearings. Figure 30 shows a cross-sectional view of a rotary liquid-piston compressor. In the rotary liquid-piston compressor, flow of compressed air or gas is discharged in a uniform, nonpulsating stream. Compression is obtained in this machine by rotating a round, multiblade rotor freely in an ellip-

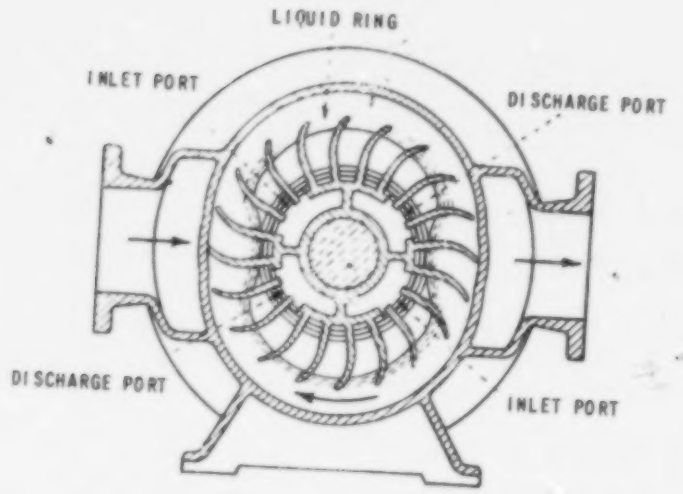


Figure 30. Rotary liquid-piston compressor (Bruce and Schubert, 1956).

tical casing partially filled with liquid. The rotating force of the multiblade rotor causes the liquid to follow the inside contour of the elliptical casing. As the liquid recedes from the rotor blades at the inlet port, the space between buckets fills with the air or gas. As the liquid reaches the narrow point of the elliptical casing, the air or gas is compressed and forced out through the discharge ports (Bruce and Schubert, 1956). Rotary liquid-piston compressors are available in sizes up to approximately 5,000 cfm. Standard single-stage units are used for pressures to 35 psig, and special single-stage units, for pressures up to 75 psig. Units are staged above 75 psig.

Dynamic Compressors

Centrifugal compressors are similar to centrifugal pumps and fans. An impeller rotates in a case, imparting a high velocity and a centrifugal motion to the gas being compressed. The impeller is mounted on a shaft supported by bearings in each end of the case. In multiple-stage compressors, several impellers are mounted on a single shaft. Passages conduct the gas from one stage to the next. Guide vanes in the passages direct the gas flow from one impeller to the next at the proper angle for efficient operation. Figure 31 shows a cross-sectional view of a typical four-stage compressor.

Since the flow of gas to the centrifugal compressor is continuous, the fundamental concepts of fluid flow apply. The gas enters at the eye of the impeller, passes through the impeller, changing in velocity and direction, and exits into the diffuser or volute, where the kinetic energy is converted to pressure (Leonard, 1956).

The centrifugal compressor generally handles a large volume of gas at relatively low pressures, but some commercially used centrifugal compressors have discharge pressures of up to 4,200 psig. These compressors are, of course, multistaged. Generally, the single-stage centrifugal compressor produces pressures up to 35 psig.

The axial-flow compressor, shown in Figure 32 is another type of dynamic compressor. It is distinguished by the multiplicity of its rotor and stator blades. These are either forged, machined, or precision cast into airfoil shapes. The compressor casing is made of cast iron, or fabricated out of steel, depending upon inlet volume, pressure ratio, and temperature conditions. Stator blades are attached to the casing to direct the flow of gas through the case.

The rotor is a drum with blades mounted around its periphery. The drum is mounted on the shaft supported by bearings in each end of the case. As the rotor turns, the blades force air through the compressor in an action similar to that of the propeller fan. The stator blades control the direction of the air as it leaves the rotor blades. Pressure is increased owing to the kinetic energy given to the gas, and the action of the gas on the stator blades. Axial-flow compressors are high-speed high-volume machines. The pressures attained are relatively low, with a maximum commercially used discharge pressure of 90 psig. These compressors are rarely used for inlet capacities below 5,000 cfm (Claude, 1956).

Reciprocating Compressors

Reciprocating compressors are positive-displacement machines used to increase the pressure of a definite volume of gas by volume reduction (Case, 1956). Most reciprocating compressors used in heavy industrial production and continuous chemical processing are stationary, water-cooled, double-acting units (see Figure 33). The basic running-gear mechanism is of the crank-and-flywheel type enclosed in a cast-iron frame. The crosshead construction permits complete separation of the compression cylinder from the crankcase, an ideal feature for handling combustible, toxic, or corrosive gases. Generally, the cylinder is double acting, that is, compression occurs alternately in the head and crank end of the cylinder. The cylinder and its heads are usually water cooled to reduce thermal stresses and dissipate part of the heat developed during compression. Compression rings on the pistons seal one end of the cylinder from the other. The piston rod is sealed in the cylinder by highly effective packing, and any slight leakage may be collected in a vent gland for return to suction or for venting to the atmosphere.

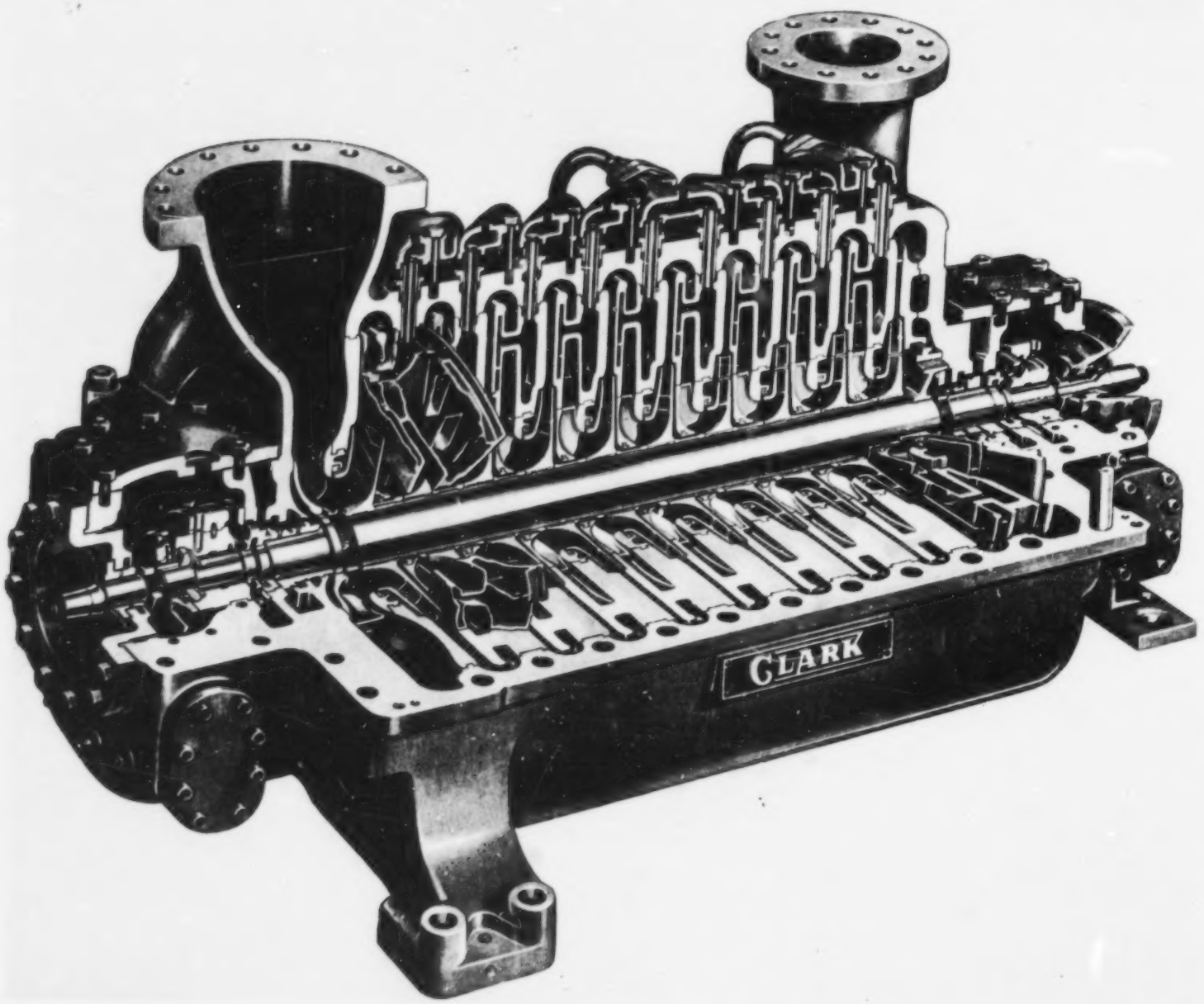


Figure 31. Cross-section of a typical four-stage centrifugal compressor (Clark Bros. Co., Olean, N.Y., from Leonard, 1956).

Gas being compressed enters and leaves the cylinder through the voluntary valves, which are actuated entirely by the difference in pressure between the interior of the cylinder and the outside system. Upon entering the cylinder, the gas may be compressed from the initial to the desired final pressure in one continuous step, that is, single-stage compression. Alternatively, multistage compression divides the compression into a series of steps or stages, each occurring in an individual cylinder. Here the gas is usually cooled between the various stages of compression.

The compression process is fundamentally isentropic (perfectly reversible adiabatic), with certain actual modifications or losses that may be considered as efficiencies related to the isentropic base. Thermal dynamic losses within the cylinder, including fluid friction losses through the valves, heating of the gas on admission to the cylinder, and irreversibility of the process, may be grouped under the single term compression efficiency. Mechanical friction losses encountered in the piston rings, rod packings, and frame bearings are grouped under the term mechanical efficiency. Thus, the overall efficiency of the compressor is the product of compression and mechanical efficiency.

For given service, the actual brake horsepower requirement of the compressor is normally about 18 to 33 percent greater than the calculated ideal

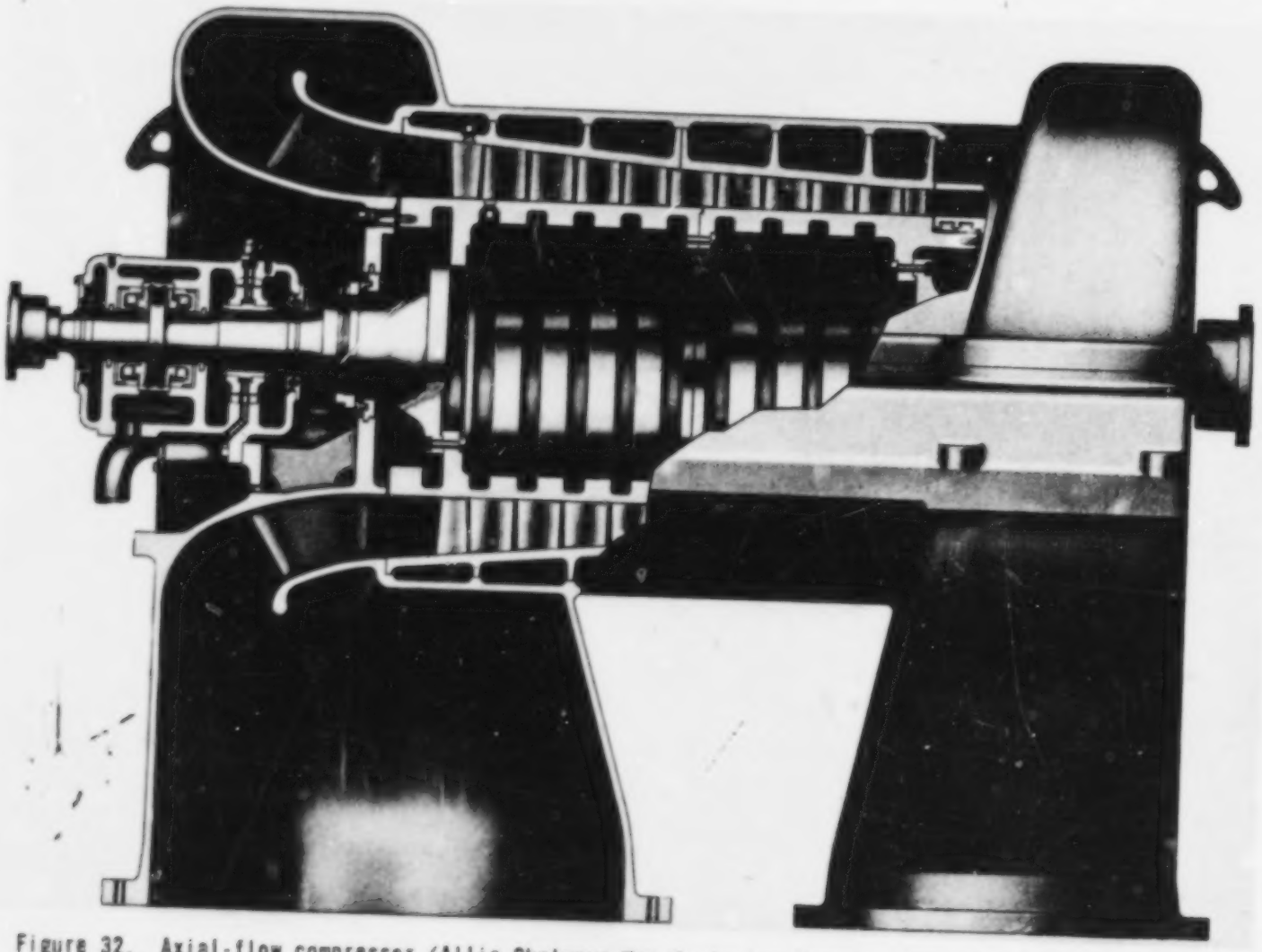


Figure 32. Axial-flow compressor (Allis-Chalmers Manufacturing Company, Milwaukee, Wisconsin, from Claude, 1956).

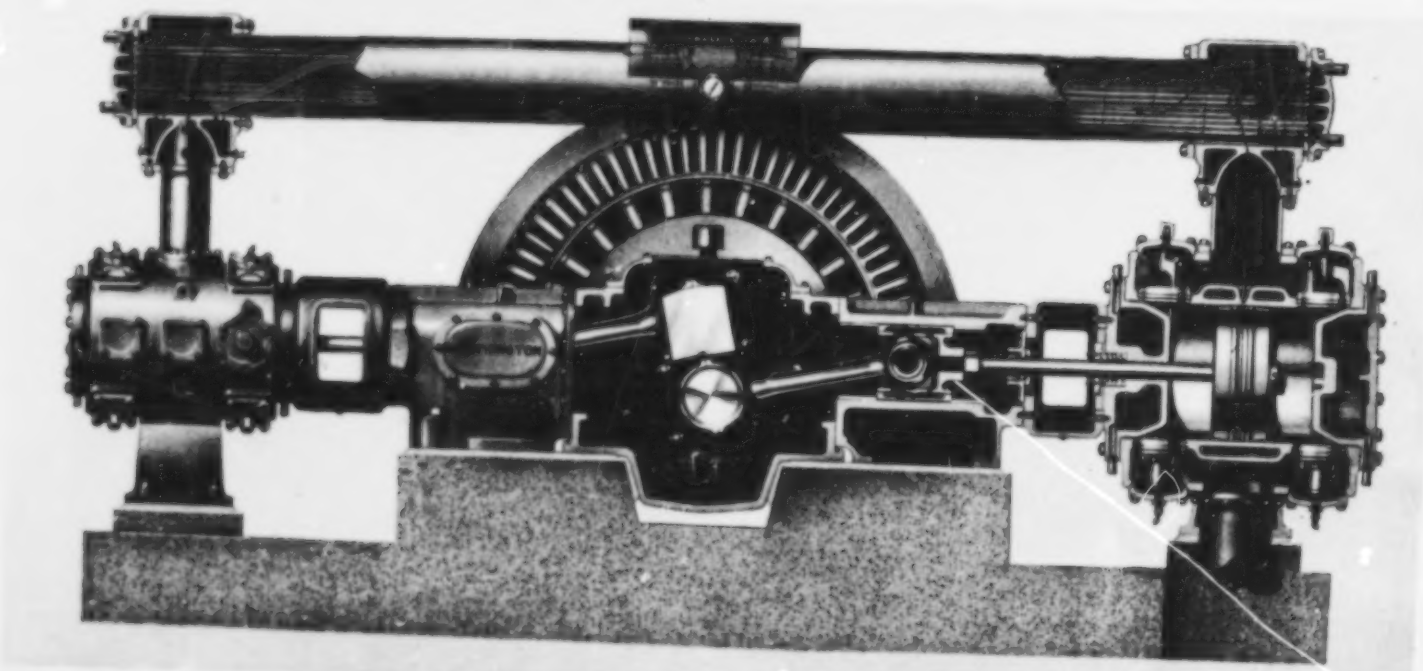


Figure 33. Four-cylinder, horizontal, balanced, opposed, synchronous-motor compressor (Worthington Corporation, Harrison, N.J., from Case, 1956).

isentropic horsepower. Or, stated another way, the overall efficiency of most compressors is in the range of 75 to 85 percent.

USE IN AIR POLLUTION CONTROL

Compressors are used to transport vapors or gases from their source and deliver them to a control device or system under pressure. In some cases, the vapors or gases can be pressurized directly to a holding vessel and then a compressor is used to send the vapors to control equipment.

The vapors created from the refining, storing, and bulk loading of volatile petroleum products are being controlled by the use of compressors. The compressors deliver the vapors under pressures ranging from 5 to 200 psig to plant fuel systems, process streams, or absorption systems.

Centrifugal, reciprocating, and rotary-lobe compressors are being used for controlling air contaminants. Single-stage reciprocating machines are the most common. Two-stage compressors developing pressures up to 200 psig are in use.

CHECKING OF EXHAUST SYSTEM

Air flow measurements and test data are necessary to determine whether an exhaust system is functioning properly and in compliance with design specifications. Correct testing procedures must be established to obtain measurements for determining whether an exhaust system has sufficient capacity for additional hoods, and also to obtain operational data from existing installations for designing future exhaust systems.

THEORY OF FIELD TESTING

For most purposes the most important factor is the accurate measurement of air quantity. Most field meters measure velocity rather than quantity. This necessitates equating velocity to quantity. By using equation 8 and a velocity meter, the quantity of air flowing through an exhaust system can be accurately measured.

Quantity Meters

Some examples of quantity meters are thin-plate orifices, sharp-edged orifices, and venturi meters. These meters are used extensively in laboratory studies, but infrequently in industrial exhaust systems.

Velocity Meters

Velocity meters are more commonly used in the field for determining air velocities. The most accurate and widely accepted in engineering practices are the pitot tube and the swinging-vane velocity meter.

PITOT TUBES

For determining air velocity, the standard pitot tube, named for the man who discovered the principle, is considered reliable and is generally accepted in engineering practice. It is the most widely used field method for determining air velocity.

A standard pitot tube (Figure 34) consists of two concentric tubes: the inner tube measures the impact pressure, which is the sum of the static and kinetic pressures, while the outer tube measures only the static pressure. When the two tubes are connected across a U-tube manometer or other suitable pressure-measuring device, the static pressure is nullified automatically and only the velocity pressure (kinetic pressure) is registered. The velocity is correlated to the velocity pressure by the equation

$$v = 1096.5\sqrt{\frac{h_v}{\rho}} \qquad (31)$$

where

v = velocity, fpm

h_v = velocity pressure (manometer reading), in. WC

ρ = density of air, lb/ft^3.

Clearly, below 1,266 fpm, the velocity pressure becomes extremely low and is, therefore, difficult to read accurately on a manometer. With a

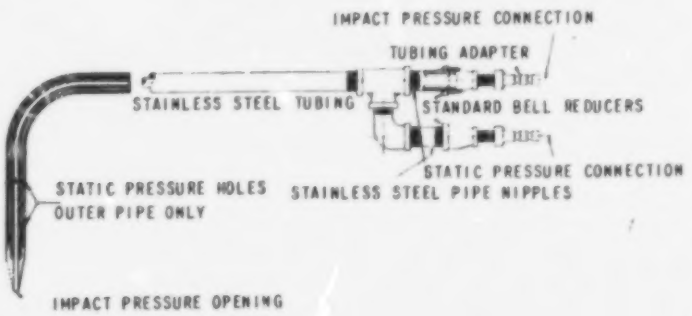


Figure 34. Standard pitot tube (Western Precipitation, Division of Joy Manufacturing Co., Los Angeles, Calif., from ASHRAE Guide and Data Book, 1963).

U-tube manometer, the accuracy is low for velocities below 2,500 fpm. With a carefully made, accurately leveled, inclined manometer, velocities as low as 600 fpm can be determined satisfactorily, but field conditions ordinarily make this procedure difficult (ASHRAE Guide and Data Book, 1963).

Pitot Tube Traversing Procedure

Since the velocity in a duct is seldom uniform across any cross section and since each pitot tube reading determines the velocity at only one localized point, a traverse of the duct is necessary in order to compute the average velocity and thus determine air flow accurately. Suggested pitot tube locations for traversing round and rectangular ducts are shown in Figure 35.

The velocity in a duct varies greatly. It is generally lowest near the edges or corners and greatest in the central portion. Because of this fluctuation, a large number of readings must be taken to determine the true average velocity. In round ducts, not less than eight readings should be taken along two diameters at centers of equal annular areas. Additional readings are necessary when ducts are larger than 1 foot in diameter. In rectangular ducts, the readings should be taken in the center of equal areas over the cross section of the duct. The number of spaces should be taken as depicted in Figure 35. In determining the average velocity in the duct, the velocity pressure readings are converted to velocities; the velocities, not the velocity pressures, are averaged to compute the average duct velocities.

Disturbed flow will give erroneous results; therefore, whenever possible, the pitot tube traverse should be made at least 7.5 duct diameters downstream from any major air stream disturbances such as a branch entry, fitting, or supply opening (ASHRAE Guide and Data Book, 1963).

Altitude and Temperature Corrections for Pitot Tubes

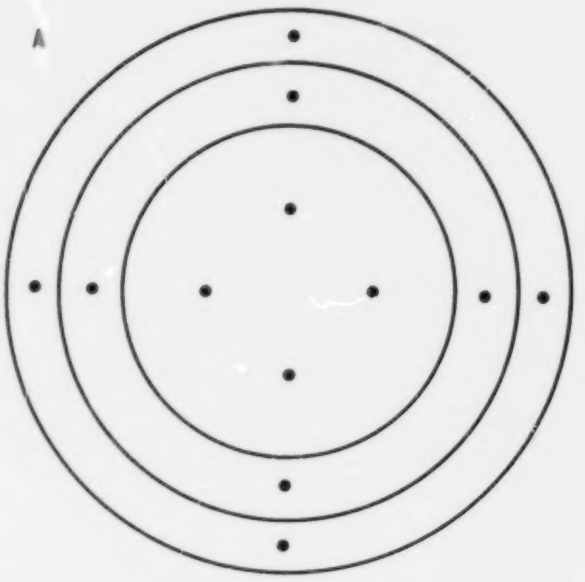
If the temperature of the air stream is more than 30° above or below the standard temperature of 70°F, or if the altitude is more than 1,000 feet, or if both conditions hold true, make a correction for density change as follows:

$$\text{Corrected velocity pressure} = \text{measured } h_v \times \frac{1}{\rho'} \qquad (32)$$

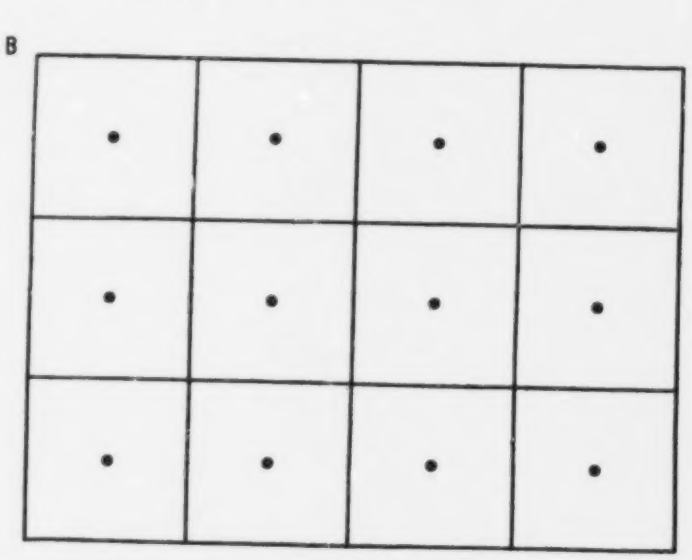
where

h_v = velocity pressure, as determined by pitot tube, in. WC

ρ' = relative density of air, at the measured condition, lb/ft^3.



Cross section of a circular stack divided into three concentric, equal areas, showing location of traverse points. The location and number of these points for a stack of given diameter can be determined from Tables 22 and 23.



Cross section of a rectangular stack divided into 12 equal areas, with traverse points located at the center of each area. The minimum number of test points is shown in Table 24.

Figure 35. Pitot tube traverse for round and rectangular ducts.

SWINGING-VANE VELOCITY METER

The factors that make the swinging-vane velocity meter an extensively used field instrument are its portability, instantaneous reading features, and

Table 22. SUGGESTED NUMBER OF EQUAL AREAS FOR VELOCITY MEASUREMENT IN CIRCULAR STACKS

Stack diameter, ft	Number of equal areas
1 or less	2
1 to 2	3
2 to 4	4
4 to 6	5
over 6	6 or more

Table 23. PERCENT OF CIRCULAR STACK DIAMETER FROM INSIDE WALL TO TRAVERSE POINT

Point number	Number of areas selected				
	2	3	4	5	6
1	6.7	4.4	3.3	2.5	2.1
2	25.0	14.7	10.5	8.2	6.7
3	75.0	29.5	19.4	14.6	11.8
4	93.3	70.5	32.3	22.6	17.7
5	--	85.3	67.7	34.2	25.0
6	--	95.6	80.6	65.8	35.5
7	--	--	89.5	77.4	64.5
8	--	--	96.7	85.4	75.0
9	--	--	--	91.8	82.3
10	--	--	--	97.5	88.2
11	--	--	--	--	93.3
12	--	--	--	--	97.9

Table 24. MINIMUM NUMBER OF TEST POINTS FOR RECTANGULAR DUCTS

Cross sectional area, ft^2	Number of test points
< 2	4
2-25	12
> 25	20

wide-range scale. The instrument is fairly rugged, and its accuracy is suitable for most field velocity determinations.

The meter consists of a pivoted vane enclosed in a case, against which air exerts a pressure as it passes through the instrument from an upstream to a downstream opening; movement of the vane is resisted by a hair spring and damping magnet. The instrument gives instantaneous readings of directional velocities on the indicating scale.

Calibrating the Velocity Meter

Before using a meter, check the zero setting. If the pointer does not come to rest at the zero position, turn the zero adjuster to make the necessary corrections. The meter with its fittings is calibrated as a unit; therefore, fittings cannot be interchanged from one meter to another. The serial number on the fittings and on the meter must agree. If a meter was originally calibrated for a filter, it must always be used. Only connecting tubing of the same length and inside diameter as that originally supplied with the meter should be used, since changes in tubing affect the calibration of the meter (Industrial Ventilation, 1956).

When the temperature of an air stream varies more than 30° from the standard temperature of 70°F, or the altitude is more than 1,000 feet, or when both conditions are fulfilled, it is advisable to make a correction for temperature and pressure. Other correction factors, as shown in Table 25 should also be used (Industrial Ventilation, 1956).

Table 25. SOME CORRECTION FACTORS FOR THE SWINGING-VANE VELOCITY METER (Industrial Ventilation, 1960)

Opening	Correction factor
Pressure opening[a]	
Hold meter jet against grille (use gross area) more than 4 in. wide and up to 600 in.^{2} area, free opening 70% or more of gross area. Hold meter jet against grille (use free-open area)	0.93
Hold meter jet 1 inch in front of grille (use gross area)	1.00
Suction opening[b]	
Square punched grille (use free-open area)	0.88
Bar grille (use gross area)	0.78
Strip grille (use gross area)	0.73
Free open, no grille	1.00

[a]For pressure openings, it is advisable to use the grille manufacturer's coefficient of discharge.

[b]For suction openings, hold meter jet perpendicular to the opening, with the tip in the same plane as the opening. This is very important because velocities are changing very rapidly in front of a suction opening.

Note: volume, cfm = area, ft^2 x air velocity, fpm x correction factor.

Uses of the Velocity Meter

Some uses of the meter and fittings are illustrated in Figure 36. On large (at least 3 ft^2) supply openings, where the instrument itself will not seriously block the opening and where the velocities are low, hold the instrument itself in the air stream, the air impinging directly in the left-hand port. When the opening is smaller than 3 square feet, or the velocities are above the no-jet scale, or when both conditions hold true, appropriate fittings must be used. On modern air-conditioning grilles, the meter or fitting should be held between 1 and 2 inches in front of the grille.

If the exhaust opening is large (at least 3 ft^2) and the air velocities are low, as in spray booths, chemical hoods, and so forth, the meter itself can be held in the air stream. The instrument should be held so that the left-hand port of the meter is flush with the exhaust opening. When the opening is smaller than 3 square feet, or the velocities are above the no-jet scale, or when both conditions hold true, appropriate fittings must be used (Industrial Ventilation, 1956).

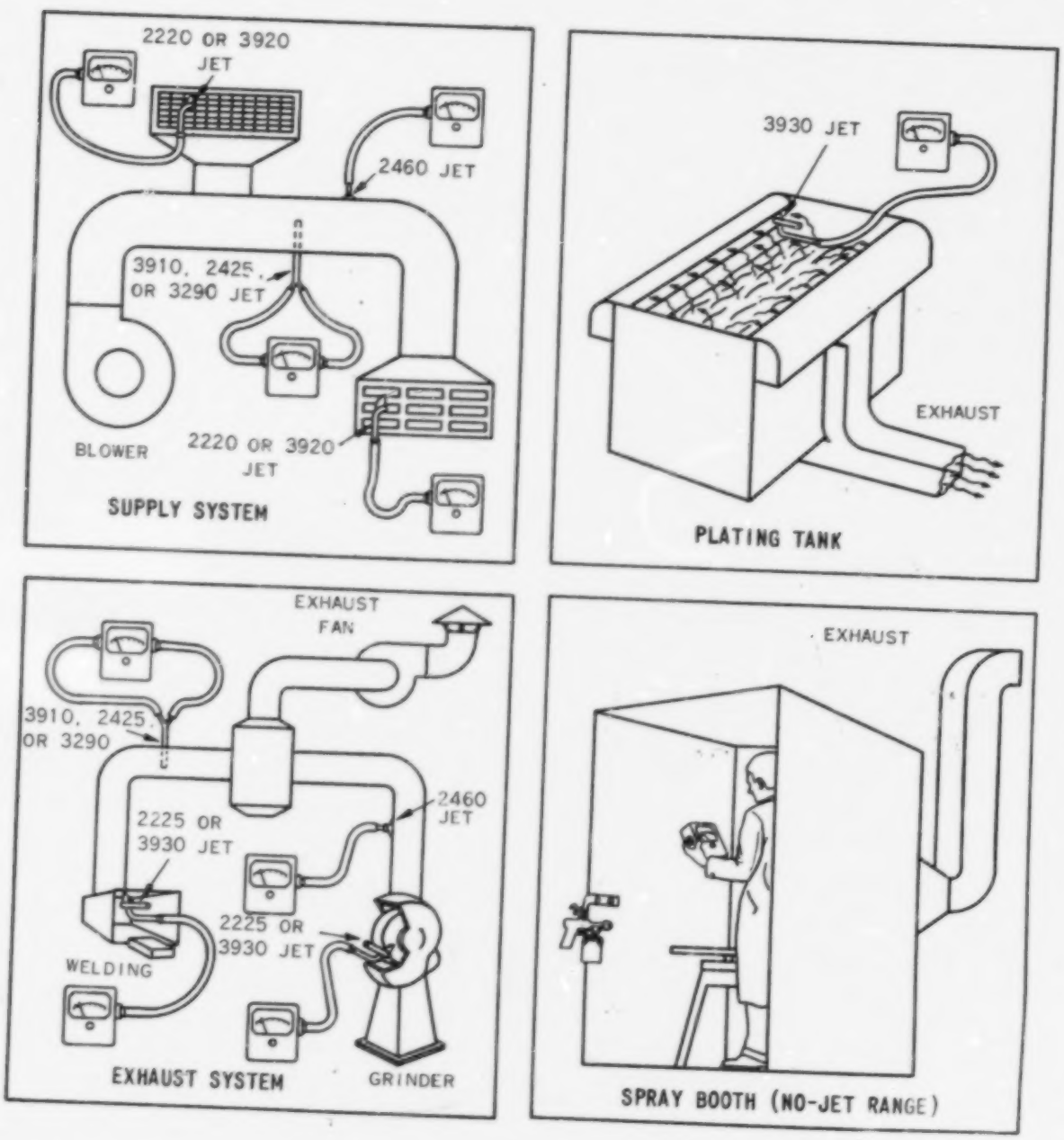


Figure 36. Some swinging-vane velocity meter applications (Industrial Ventilation, 1960).

COOLING OF GASEOUS EFFLUENTS

When designing an air pollution control system, the designer must know the temperatures of the gases to be handled before he can specify the materials of construction for the system, the size of ductwork, the size of the blower, and the type of air pollution control device. Often, hot gases must be cooled before being admitted to the control device. The cooling equipment will add to the resistance of the flow of gases through the exhaust system and may affect the volume and composition of the gases. Since the gases must pass through the cooling device, it must be designed as an integral part of the exhaust system.

METHODS OF COOLING GASES

Although there are several methods of cooling hot gases, those most commonly used in air pollution control systems are: (1) Dilution with ambient air, (2) quenching with water, and (3) natural convection and radiation from ductwork. In a few cases, forced-draft heat exchangers, air cooled and water cooled, have been used.

With the dilution method, the hot gaseous effluent from the process equipment is cooled by adding sufficient ambient air to result in a mixture of gases at the desired temperature. Natural convection and radiation occur whenever there is a temperature difference between the gases inside a duct and the atmosphere surrounding it. Cooling hot gases by this method requires only the provision of enough heat transfer area to obtain the desired amount of cooling. The water quench method uses the heat of vaporization of water to cool the gases. Water is sprayed into the hot gases under conditions conducive to evaporation, the heat in the gases evaporates the water, and this cools the gases. In forced-draft heat exchangers, the hot gases are cooled by forcing cooling fluid past the barrier separating the fluid from the hot gases.

Dilution With Ambient Air

The cooling of gases by dilution with ambient air is the most simple method that can be employed. Essentially, it involves the mixing of ambient air with a gas of known volume and temperature to produce a low-temperature mixture that can be admitted to an air pollution control device. In designing such a system, first determine the volume and temperature of air necessary to capture and convey the air contaminants from a given source. Then calculate the amount of ambient air required to provide a mixture of the desired temperature. The air pollution control device is then sized to handle the combined mixture.

Although little instrumentation is required, a gas temperature indicator with a warning device, at the very least, should be used ahead of the air pollution control device to ensure that no damage occurs owing to sudden, unexpected surges of temperature. The instrumentation may be expanded to control either the fuel input to the process or the volume of ambient air to the exhaust system.

This method of cooling hot gases is used extensively where the hot gases are discharged from process equipment in such a way that an external hood must be used to capture the air contaminants. The amount of air needed to ensure complete capture of the air contaminants is generally sufficient to cool the gases to approximately 500°F, which permits the use of high-temperature air pollution control devices. When the volume of hot gases is small, this method may be used economically even when much more air is needed to achieve the desired cooling than that needed for adequate capture of air contaminants.

When large volumes of hot gases require cooling, the size of the exhaust system and control device becomes excessively large for dilution cooling. In any case, compare the costs of installation and operation of the various cooling methods before deciding which method to use.

The following examples illustrate (1) a method of determining the resultant temperature of the mixture of the hot furnace gases and the ambient air induced at the furnace hood, and (2) a method of determining the volume of air needed to cool the hot furnace gases to a selected temperature.

Example 14

Given:

Yellow-brass-melting crucible furnace. Fuel burned: 1,750 cfh natural gas with 20 percent excess air.

Maximum gas temperature at furnace outlet: 2,500°F.

Volume of dilution air drawn in at the furnace hood: 4,000 cfm.

Maximum temperature of dilution air: 100°F.

For this problem, neglect the heat losses due to radiation and natural convection from the hood and ductwork. Assume complete combustion of the fuel.

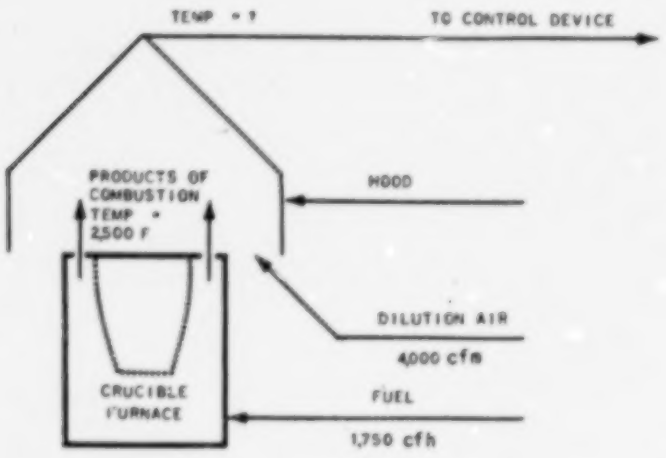


Figure 37. Problem: Determine the temperature of the gases entering the control device.

Solution:

1. Determine the weight (W) and heat (Q) above 60°F in the products of combustion (PC):

$$Q = \Sigma Q_i$$

$$W = \Sigma W_i$$

$$Q_i = W_i h_i$$

where

W_i = weight of individual gas flowing, lb/min

h_i = enthalpy above 60°F of each gas, Btu/lb

Q_i = heat above 60°F in each gas, Btu/min

Convert fuel rate to cfm $\frac{1,750}{60} = 29.17$ cfm

Referring to the calculation data of Table 26, $W_i = 29.14$ lb/min and $Q_i = 21,470$ Btu/min

2. Heat above 60°F in 4,000 cfm of dilution air entering hood at 100°F:

Density of air at 100°F = 0.0708 lb/ft^3 (from Table D1, Appendix D)

Enthalpy of air at 100°F = 9.6 Btu/lb (from Table D3, Appendix D)

Weight of dilution air = (4,000)(0.0708) = 283.2 lb/min

Heat above 60°F in dilution air = (9.6)(283.2) = 2,720 Btu/min

3. Enthalpy of mixture of PC and dilution air:

Total weight of mixture = 29.14 + 283.2 = 312.3 lb/min

Heat above 60°F in mixture 21,470 + 2,720 = 24,190

Enthalpy of mixture = $\frac{24,190}{312.3} = 77.4$ Btu/lb

4. Temperature of mixture:

To determine the temperature of the mixture, determine the enthalpy of the mixture at two temperatures, preferably above and below the calculated enthalpy of 77.4 Btu/lb.

Table 26. CONVERSION VALUES FOR ITEM 1, EXAMPLE 14

PC per cubic foot of fuel		PC from furnace	Enthalpy of component	Heat above 60°F in component
Component	Weight, lb/ft^3	W_i, lb/min	h_i at 2,500°F, Btu/lb	Q_i, Btu/min
CO_2	0.132[a]	3.85[b]	690.2[c]	2,660[d]
H_2O	0.099	2.89	1,318.1	3,810
N_2	0.731	21.32	672.3	14,330
O_2	0.037	1.08	621.0	670
Totals		29.14		21,470

[a] From Table D7, Appendix D.
[b] W_i = (0.132 lb/ft^3)(29.17 ft^3/min) = 3.85 lb/min
[c] From Table D3, Appendix D.
[d] Q_i = (3.85 lb/min)(690.2 Btu/lb) = 2,660 Btu/min

Then, by interpolation, the temperature corresponding to 77.4 Btu/lb can be determined. Since the mixture contains mostly nitrogen, the enthalpies should be close to those of nitrogen. From Table D3 it appears that the mixture temperature will be between 350°F and 400°F. The enthalpy of the mixture, H_m, is:

$$h_m = \frac{Q_m}{W_m} \quad \text{at desired temperatures}$$

where

$$W_m = \Sigma W_i$$
$$Q_m = \Sigma W_i h_i$$

The O_2 and N_2 from the dilution air must be added to the O_2 and N_2 from the PC.

Weight of dilution air = 283.2 lb/min

O_2 content = (283.2)(0.21) = 59.5 lb/min
N_2 content = (283.2)(0.79) = 223.7 lb/min

Referring to the calculation data of Table 27:

h_m at 350°F = $\frac{22,530}{312.3}$ = 72.1 Btu/lb

h_m at 400°F = $\frac{26,150}{312.3}$ = 83.6 Btu/lb.

By interpolation the mixture temperature = 373°F

Therefore, the exhaust system and control device must be designed to handle gases at 373°F.

Example 15

Problem:

Using the same given data in Problem No. 1, determine the amount of dilution air required to reduce the temperature of PC to 300°F.

Solution:

1. Heat above 60°F in PC at 2,500°F = 21,470 Btu/min (From Table 26)

2. Heat lost by PC in cooling from 2,500° to 300°F: From Table 26 obtain the weight (W_i) of each component of PC discharged from the furnace. From Table D3, obtain the enthalpy (h_i) of each component at 300°F. Referring to the calculation data of Table 28: Heat to be lost = 21,470 - 1,847 = 19,623 Btu/min

3. Volume of air needed to cool PC to 300°F:

   Air inlet temperature = 100°F (given)
   Final air temperature = 300°F

   h at 100°F = 9.6 Btu/lb (from Table D3)
   h at 300°F = 57.8 Btu/lb (from Table D3)

   Δh = 48.2 Btu/lb

   Weight of air needed = $\frac{19,623}{48.2}$ = 408 lb/min

Table 27. CONVERSION VALUES FOR ITEM 4, EXAMPLE 14

Component	W_i, lb/min	h_i [d] at 350°F, Btu/lb	h_i [d] at 400°F, Btu/lb	$Q_i = h_i W_i$ at 350°F, Btu/min	$Q_i = h_i W_i$ at 400°F, Btu/min
CO_2	3.85	63.1	74.9	242.9[e]	288.4
H_2O	2.89	131.3	154.3	379.2	455.6
N_2	245.02[a]	73.3	84.9	17,980.0	20,800.0
O_2	60.58[c]	64.8	76.2	3,925.0	4,615.0
Totals	312.3[b]			22,530	26,150

[a] W_i of N_2 is sum of N_2 from PC and dilution air.
[b] Totals are rounded off to four significant figures.
[c] W_i of O_2 is sum of O_2 from PC and dilution air.
[d] From Table D3, Appendix D.
[e] Q_i = (3.85 lb/min)(63.1 Btu/lb) = 242.9 Btu/min.

Table 28. CONVERSION VALUES

Gaseous components	W_i, lb/min	h_i at 300°F, Btu/lb	$Q_i = h_i W_i$, at 300°F Btu/min
CO_2	3.85	51.3	197.7
H_2O	2.89	108.2	312.5
N_2	21.32	59.8	1,279.0
O_2	1.08	53.4	57.5
Totals	29.14		1,846.7

Total heat above 60°F in PC at 300°F = 1,847 lb/min

Volume of dilution air at 100°F

ρ at 100°F = 0.0708 lb/ft^3 (From Table D1)

$$\text{Volume} = \frac{408}{0.0708} = 5,760 \text{ cfm}$$

The exhaust system must be designed to handle a sufficient volume of gases at 300°F to provide an indraft of dilution air of 5,760 cfm in addition to the products of combustion.

Quenching With Water

When a large volume of hot gas is to be cooled and only a small quantity of dilution air is needed to capture the air contaminants, some methods of cooling other than dilution with ambient air should be used. Since the evaporation of water requires a large amount of heat, the gas can be cooled simply by spraying water into the hot gas.

For efficient evaporation of water in a gas stream, it has been determined that the gas velocity should be from 500 to 700 fpm and the entire cross section of the stream should be covered with a fine spray of water. If, however, water carryover is undesirable, as in a baghouse, satisfactory settling of the water droplets must be attained; hence, lower velocities are employed. Eliminator plates are seldom used in installations where excessive maintenance due to corrosion or fouling is expected. To reduce further the likelihood of water droplet carryover, place the water spray chamber as far from the baghouse as practical.

Water spray pressures generally range from 50 to 150 psig; however, to reduce the amount of moisture collected, some installations have employed pressures as high as 400 psig. Since the moisture collected in spray chambers readily corrodes steel, the chambers are frequently lined with materials resistant to corrosion.

If the gases discharged from the basic equipment are exceptionally hot, as are those from the cupola furnace, the first portion of the duct should be refractory lined or made from stainless steel. In some cases, stainless steel ducts with water sprays have been used between the furnace and the quench chamber.

For controlling the gas temperature leaving the quench chamber, a temperature controller is generally used to regulate the amount of water sprayed into the quench chamber. For emergency conditions, a second temperature controller can be used to divert excessively hot gases away from the air pollution control device.

Cooling hot gases with a water quench is relatively simple and requires very little space. Figure 38 shows a quench chamber used to cool the gas-

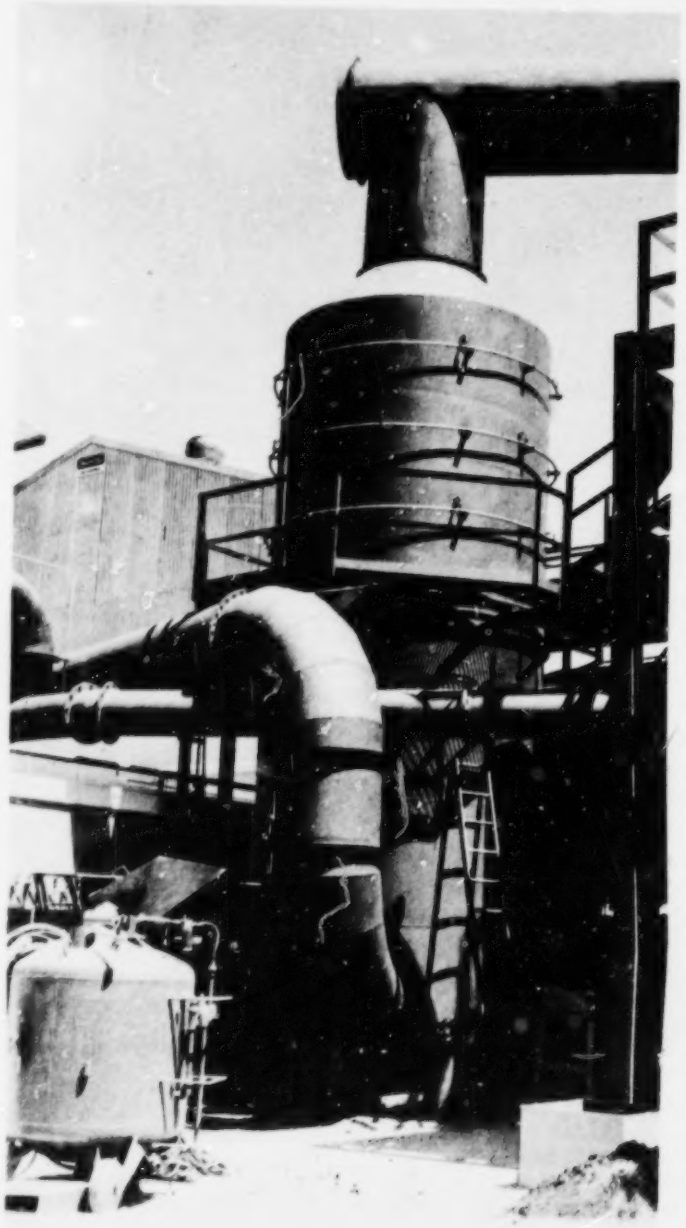


Figure 38. A quench chamber in a baghouse control system serving a cupola furnace (Harsell Engineering Company, Inglewood, California).

eous effluent from a cupola furnace. Quench chambers are little more than enlarged portions of the ductwork equipped with water sprays. They are easy to operate and, with automatic temperature controls, only that amount of water is used that is needed to maintain the desired temperature of the gases at the discharge. Their installation and operating costs are generally considered to be less than for other cooling methods. Quench chambers should not be used when the gases to be cooled contain a large amount of gases or fumes that become highly corrosive when wet. This creates additional maintenance problems, not only in the quench chamber, but in the remainder of the ductwork, the control device, and the blower.

The following example will illustrate some of the factors that must be considered when designing a quench chamber to cool the gaseous effluent from a gray-iron-melting cupola.

Example 16

Given:

32-in.-I. D. cupola. Maximum temperature of gaseous effluent at cupola outlet = 2,000°F.

Weight of gaseous effluent at cupola outlet = 216 lb/min.

Volume of gaseous effluent at cupola outlet = 13,280 cfm at 2,000°F. This volume of effluent includes indraft air at the charging door of the cupola. The temperature of 2,000°F is a maximum temperature.

Assume the effluent gases have the same properties as air. Consideration of the enthalpies of the gaseous constituents in the effluent gas stream will show that this is a valid assumption. Any corrections would introduce an insignificant refinement to the calculations when considered with respect to the accuracy of other design factors.

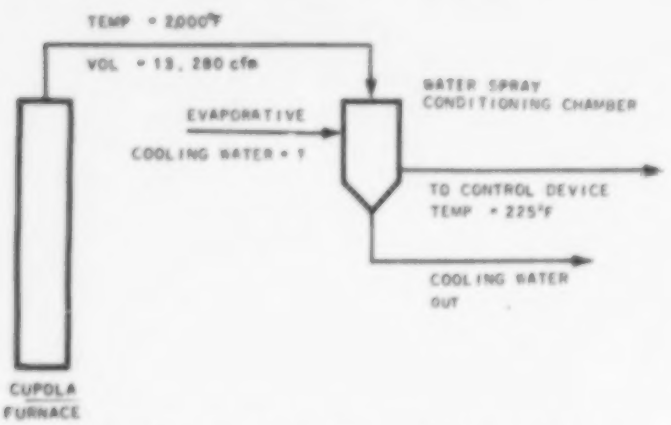


Figure 39. Problem: Determine the water needed to cool the gaseous effluent to 225°F and the total volume of gases discharged from the quench chamber.

Solution:

1. Cooling required:

Enthalpy of gas at 2,000°F = 509.5 Btu/lb
Enthalpy of gas at 225°F = 39.6 Btu/lb
Δh = 469.9 Btu/lb

(216)(469.9) = 101,300 Btu/min

2. Water to be evaporated:

Heat absorbed per lb of water:

$Q = h_g$ (225°F, 14.7 psig) - hf (60°F)

= 1,156.8 - 28.06 = 1,128.7 Btu/lb

$$\text{Water required} = \frac{101,300}{1,128.7} = 90 \text{ lb/min}$$

3. Volume of water evaporated at 225°F:

$$\frac{379}{18}\left(\frac{460 + 225}{460 + 60}\right)(90) = 2,510 \text{ cfm}$$

4. Total volume vented from spray chamber at 225°F:

$$\text{Cupola} = (13,280)\left(\frac{225 + 460}{2,000 + 460}\right) = 3,700 \text{ cfm}$$

Water = 2,510 cfm

Total = 6,210 cfm

Problem Note: In this example, the calculated amount of water required to cool the gases, 90 lb/min or 10.8 gal/min, is only the water that must be evaporated. Since all the water sprayed into a quench chamber does not evaporate, the pump and spray system should be sized to supply more water than that calculated. The amount of excess water needed will depend on factors such as the inlet temperature of the gases, the temperature drop required, the fineness of the water spray, and the arrangement of spray heads. It is not uncommon to size the pump to give 200 percent of the water needed for evaporation. The actual amount of water used should be controlled by the temperature of the gases discharged from the quench chamber.

The loss of heat by radiation and convection from the ducts was neglected. With long duct runs, however, a considerable temperature drop in the gas-

eous effluent could occur, especially if the quench chamber was installed near the downstream end of the ductwork. If the quench chamber is placed near the control device, adequate water entrainment separators must be employed.

Natural Convection and Radiation

When a hot gas flows through a duct, the duct becomes hot and heats the surrounding air. As the air becomes heated, natural drafts are formed carrying the heat away from the duct. This phenomenon is called natural convection. Heat is also discharged from the hot duct to its surroundings by radiant energy.

The rate of heat transfer is a function of the resistances to heat flow, the mean temperature difference between the hot gas and the air surrounding the duct, and the surface area of the duct. It may be expressed as:

$$Q = UA\,\Delta t_m \qquad (33)$$

where

Q = rate of heat transfer, Btu/hr

U = overall heat transfer coefficient, Btu/hr-°F-ft^2

A = heat transfer area, ft^2

Δt_m = log-mean temperature difference, °F.

The rate of heat transfer is determined by the amount of heat to be removed from the hot gaseous effluent entering the exhaust system. For any particular basic process, the weight of gaseous effluent and its maximum temperature are fixed. The cooling system must, therefore, be designed to dissipate sufficient heat to lower the effluent temperature to the operating temperature of the air pollution control device to be used.

The rate of heat transfer can be determined by the enthalpy difference of the gas at the inlet and outlet of the cooling system.

$$Q = W\Delta h \qquad (34)$$

where

W = weight of gas flowing, lb/hr

Δh = enthalpy change between inlet and outlet, Btu/lb.

The log-mean temperature difference is the difference in temperature between the air surrounding the duct, and the inlet and outlet temperature of the gas. This term, too, is fixed for a particular process. It is calculated as follows:

$$\Delta t_m = \frac{(t_1 - t_a) - (t_2 - t_a)}{\log_e \frac{(t_1 - t_a)}{(t_2 - t_a)}} \qquad (35)$$

where

t_1 = gas temperature of inlet, °F

t_2 = gas temperature at outlet, °F

t_a = air temperature, °F.

In many processes the temperature of the gaseous effluent is not constant but varies during different operational phases. The atmospheric temperatures also vary a great deal. In such cases, the cooling system must be designed for the worst conditions that prevail to ensure adequate cooling at all times. The inlet temperature (t_1) chosen must be the maximum temperature of the gas entering the system; t_2 must be the maximum allowable temperature of the gas discharged from the cooling system; and t_a must be the maximum expected atmospheric temperature.

The overall coefficient of heat transfer, U, is the reciprocal of the overall resistance to heat flow. It is a function of the individual heat transfer coefficients, which can be estimated by empirical equations. U must be based on either the inside or outside surface of the duct. For radiation-convection cooling, it is generally based on the outside surface and is denoted by U_o. U_o is defined by the following equation (Kern, 1950):

$$U_o = \frac{h_{io}\, h_o}{h_{io} + h_o} \qquad (36)$$

where

h_{io} = inside film coefficient based on the outside surface area, Btu/hr-°F-ft^2

h_o = outside film coefficient, Btu/hr-°F-ft^2.

The inside film coefficient can be solved by the formula (Kern, 1950):

$$h_i = j_H \frac{k}{D} \left(\frac{C\mu}{k}\right)^{1/3} \qquad (37)$$

where

$j_H = \frac{h_i D}{k} \left(\frac{C\mu}{k}\right)^{-1/3}$ and is plotted against

Reynolds number (Re) as shown in Figure 40

k = thermal conductivity, Btu/hr-ft-°F

D = inside diameter of duct, ft

C = heat capacity, Btu/lb-°F

μ = viscosity, lb/hr-ft.

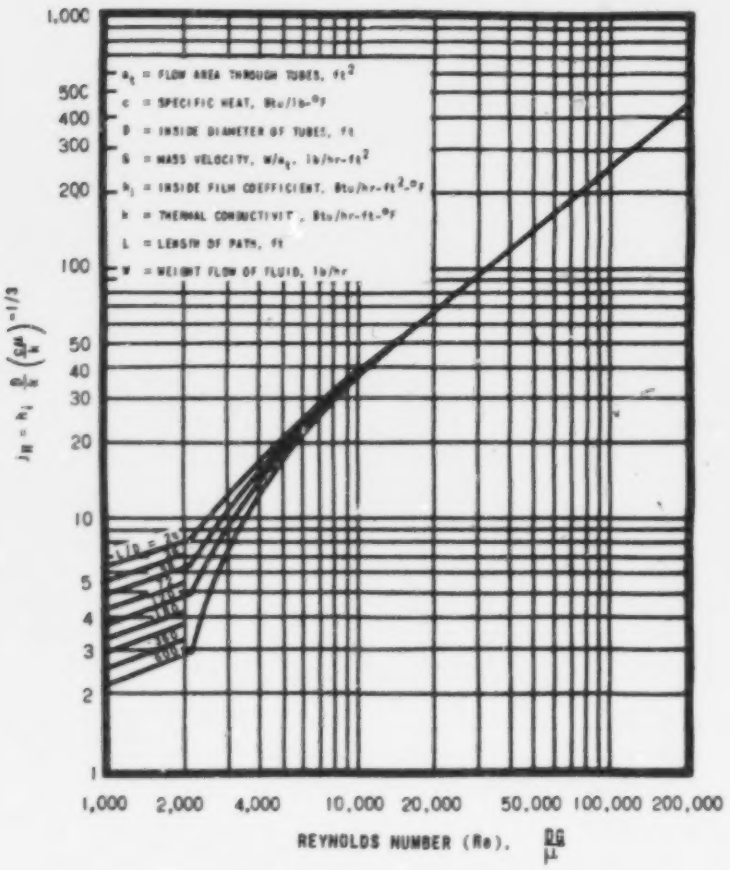


Figure 40. Tube-side heat-transfer curve (Adapted from Sieder and Tate in Kern, 1950).

The Reynolds number is a function of the duct diameter, the mass velocity, and viscosity of the gas. It is calculated by the equation

$$Re = \frac{DG_p}{\mu} \qquad (38)$$

where

G_p = mass velocity = $\frac{W}{a_p}$ lb/hr-ft^2 and

a_p = flow area inside the duct = $\frac{\pi D^2}{4}$

The inside film coefficient is a measure of the flow of heat through the inside film. An increase in h_i will, therefore, increase the rate of heat transferred from the gas to the atmosphere. It can be seen that an increase in Re will increase the rate of heat transfer. Since the weight of gas flowing is fixed, Re can be increased only by increasing the velocity of the gas. It has already been shown that an increase in velocity will increase the power required to move the gases through the exhaust system. Consequently, the optimum velocity for good heat transfer at reasonable blower-operating costs must be determined. It is known that a sacrifice in heat transfer rate to obtain lower blower horsepower results in the most economical cooling system. Owing to the many variables involved, however, each system must be calculated on its own merits.

The outside film coefficient (h_c) is the sum of the coefficient due to natural convection (h_c) and the coefficient due to radiation (h_r). An empirical equation for h_c for vertical pipes more than 1 foot high and for horizontal pipes is (McAdams, 1942):

$$h_c = 0.27 \left(\frac{\Delta t}{D_o}\right)^{0.25} \qquad (39)$$

where

Δt = the temperature difference between the outside duct wall and the air, $t_w - t_a$, °F

D_o = outside duct diameter, ft.

The radiation coefficient is computed from (McAdams, 1942):

$$h_r = \frac{\epsilon \sigma \left[T_1^4 - T_2^4\right]}{T_1 - T_2}$$

$$= 0.173 \frac{\epsilon \left[(T_1/100)^4 - (T_2/100)^4\right]}{T_1 - T_2} \qquad (40)$$

where

ϵ = emissivity of the duct surface, dimensionless

σ = Stefan-Boltzmann constant, 0.173 x 10^{-8} Btu/ft^2-h_r-°R^4

T_1 = <u>absolute</u> temperature of the duct surface, °R

T_2 = <u>absolute</u> temperature of the air, °R.

In Figure 41, T_1 is plotted against h_r for several air temperatures; h_r was calculated for an emissivity equal to 1.0. To obtain h_r for a system, multiply the h_r found from Figure 41 by the emissivity of the duct surface. Since the emissivity of

the surface is a function of the surface condition, and a black surface generally gives the highest emissivity, the ductwork should be blackened.

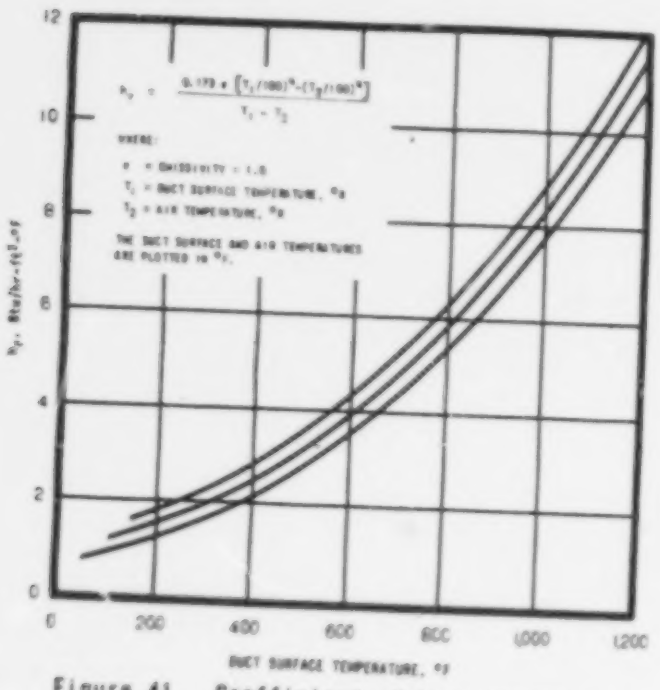


Figure 41. Coefficient of heat transfer by radiation for $\epsilon = 1.0$ (Adapted from McAdams, 1942).

When calculating h_o, assume the temperature of the duct wall (t_w) and then check. The assumed t_w can then be checked with the following equation (Kern, 1950):

$$t_w = t_m - \frac{h_o}{h_o + h_{io}} (t_m - t_a) \qquad (41)$$

where

t_m = the average gas temperature, °F.

If t_w is not the same as assumed t_w, estimate a new t_w and recalculate h_o. When the assumed t_w and calculated t_w are the same, use the corresponding h_o to calculate U_o.

The heat transfer area (A) can now be calculated. The length of duct needed to give the necessary area is then calculated by using the outside diameter used in determining the film coefficients. If the length of duct needed is large, the ductwork will probably be arranged in vertical columns to conserve floor space. Figure 42 shows such an installation serving a lead blast furnace and a lead reverberatory furnace. The columns require several 180° bends, which will offer a large resistance to the flow of gas. To minimize these losses, the gas velocity should be low, preferably less than normal dust-conveying velocities. By joining the bottoms of the columns with hoppers, any dust settling out as a result of low velocities can be collected without fouling the exhaust system. If the cooling area is such that a single loop around the plant or across a roof is sufficient, avoid sharp bends and maintain carrying velocities. When gases are cooled through a large temperature range, the volume will be reduced, so that smaller diameter ductwork may be needed as the gases proceed through the cooling system. With cooling columns, the diameter of the duct joining the last column and the air pollution control device must be sized properly to provide suitable conveying velocities for the cooled effluent.

For most convection-radiation cooling systems, the only equipment used is sufficient ductwork to provide the required heat transfer area and, of course, a blower of sufficient capacity to move the gaseous effluent through the system. Unless the temperature of the gases discharged from the basic process is exceptionally high, or there are corrosive gases or fumes present, black iron ductwork is generally satisfactory. The temperature of the duct wall can be determined for any portion of the ductwork by using the method previously described for determining t_w. If t_w proves to be greater than black iron can withstand, either use a more heat resistant material for that portion of the system or recirculate a portion of the cooled gas to lower the gas temperature at the inlet to the cooling system.

With this type of cooling, flexibility in controlling the gas temperature is limited. When either the gas stream or air temperatures, or both, are lower than design values, the gases discharged from the cooling device will be less than that calculated, and condensation of moisture from the effluent within the control device might result. Conversely, when design temperatures are exceeded, the temperature of the gases discharged from the cooling system could become too high. To avoid damage to the air pollution control device, install a quick-response temperature controller to warn the operator of the change in temperature so that proper adjustments can be made.

The radiation-convection cooling system is in operation whenever hot gases are being conducted through the exhaust system. The gases being cooled are not diluted with any cooling fluid. The exhaust system blower and the air pollution control device need not be sized for an extra volume of gases due to dilution. Since no water is used, there is no need for pumps, and corrosion problems are nonexistent. On the other hand, these cooling systems require considerable space, and blower horsepower requirements are high owing to the additional resistance to gas flow.

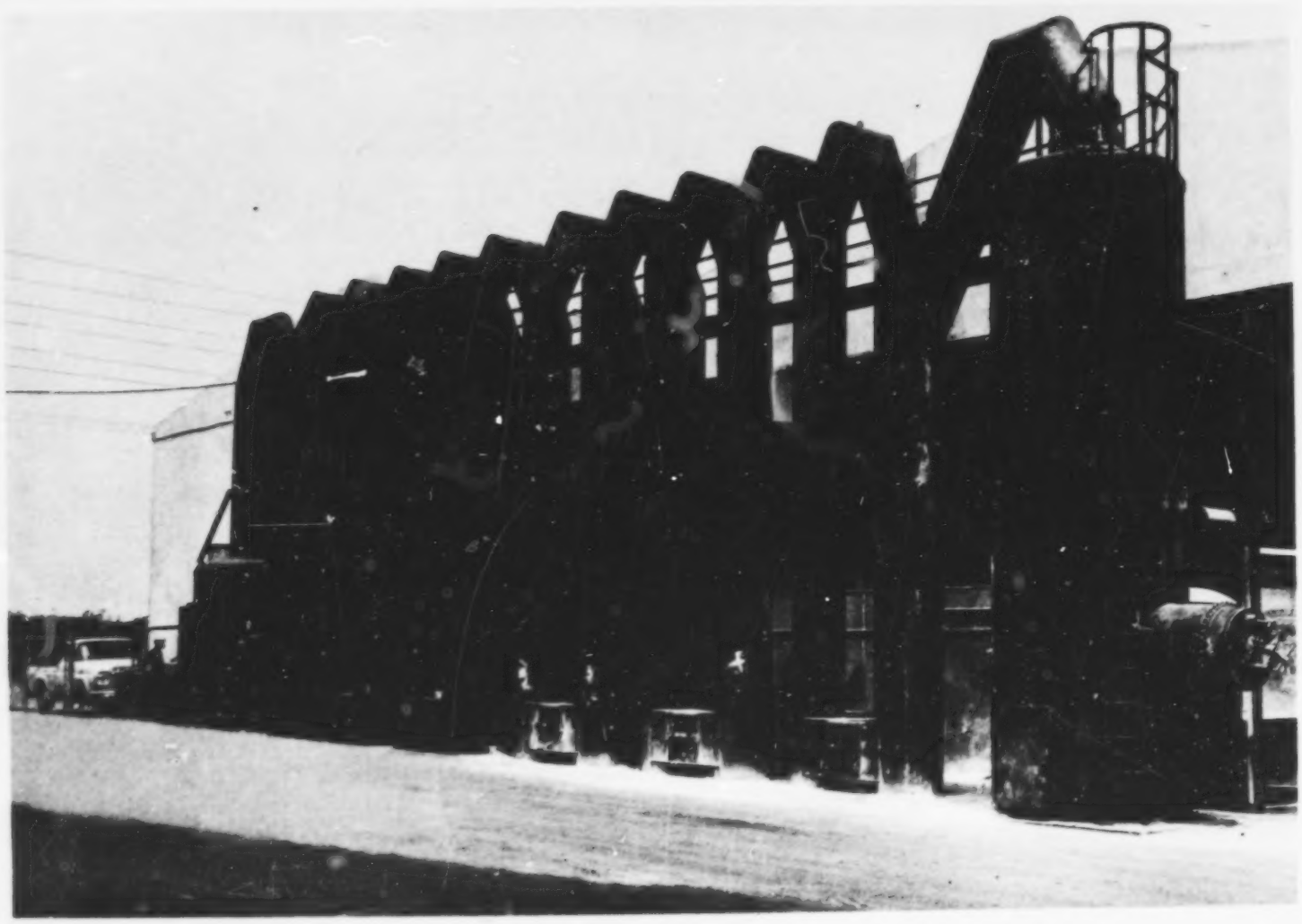


Figure 42. Radiation-convection cooling columns in an air pollution system serving a lead blast furnace and a lead reverberatory furnace (Western Lead Products Company, City of Industry, California).

The following example illustrates a method of determining the heat transfer area needed to cool the gaseous effluent from the cupola of example 16 with a natural convection-radiation cooler.

Example 17

Given:

32-in.-I. D. cupola.

Gaseous effluent = 12, 960 lb/hr.

Maximum temperature of effluent = 2, 000°F.

Volume of effluent at 2, 000°F = 13, 280 cfm. This volume of effluent includes indraft air at the charging door of the cupola. The temperature of 2, 000 °F is a maximum.

The vertical cooling columns must be located a minimum of 60 feet from the cupola.

Assume the effluent gases have the same physical properties as air. Consideration of the enthalpy, viscosity, thermal conductivity, density, and heat capacity of the gaseous constituents in the effluent gas stream will show that this is a valid assumption. Any correction would introduce an insignificant refinement to the calculations when considered with respect to the accuracy of other design factors.

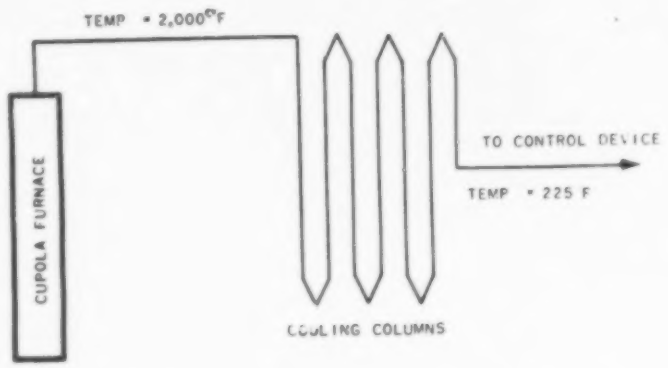


Figure 43. Problem: Determine the length of duct needed to cool the gases to 225°F by natural convection-radiation columns.

Solution:

1. Heat (Q) to be transferred:

Enthalpy of gas (2,000°F) = 509.5 Btu/lb (from Table D3, Appendix D)

Enthalpy of gas (225°F) = 39.6

$$\Delta H = 469.9$$

$$Q = (469.9)(12,960) = 6,078,000 \text{ Btu/hr}$$

2. Determine logarithmic mean temperature difference (Δt_m):

Gas inlet temperature (t_1) = 2,000°F

Gas outlet temperature (t_2) = 225°F

Cooling air temperature (t_a) = 100°F

$$t_m = \frac{(t_1 - t_a) - (t_2 - t_a)}{\log_e \frac{(t_1 - t_a)}{(t_2 - t_a)}}$$

$$= \frac{(2,000-100) - (225-100)}{\log_e \frac{1,900}{125}} = 653°F$$

3. Determine inside film coefficient (h_i):

$$h_i = j_H \frac{k}{D} \left(\frac{C\mu}{k}\right)^{1/3}$$

(a) Obtain j_H from Figure 40:

$$Re = \frac{DG_p}{\mu}$$

Using a design velocity of 3,500 fpm in the horizontal section at the cupola discharge:

$$\text{Area} = \frac{13,280 \text{ cfm}}{3,500 \text{ fpm}} = 3.79 \text{ ft}^2$$

$$\text{Pipe diameter (D)} = \left(\frac{(3.79)(4)}{\pi}\right)^{1/2} = 2.2 \text{ ft}$$

$$G_p = \frac{12,960 \text{ lb/hr}}{3.79 \text{ ft}^2} = 3,420 \text{ lb/hr-ft}^2$$

μ = 0.094 lb/hr (from Table D1)

$$Re = \frac{(2.2)(3,420)}{0.094} = 80,000$$

j_H = (See Figure 40) = 215

(b) Obtain k, C, and $\frac{C\mu}{k}$ from Table D1

k = 0.0297

C = 0.247

$$\frac{C\mu}{k} = 0.775$$

(c) Substitute above data in formula, and solve for h_i:

$$h_i = 215 \left(\frac{0.0297}{2.2}\right)(0.775)^{1/3} = 2.66 \text{ Btu/hr-ft}^2\text{-°F}$$

4. Convert h_i to inside film coefficient (h_{io}) based on outside surface area:

Use a 10-gage duct wall, thickness = 0.141 inch

$$D_o = (2.2) + \frac{(2)(0.141)}{12} = 2.224 \text{ ft}$$

$$h_{io} = (2.66)\frac{2.2}{2.224} = 2.62 \text{ Btu/hr-ft}^2\text{-°F}$$

5. Determine the outside film coefficient (h_o):

$$h_o = h_c + h_r$$

(a) $$h_c = 0.27 \left(\frac{\Delta t}{D_o}\right)^{0.25}$$

Assume a duct wall temperature of 525°F

$$h_c = 0.27\left(\frac{425}{2.224}\right)^{0.25} = 1.00 \text{ Btu/hr-ft}^2\text{-°F}$$

(b) Obtain h_r from Figure 41:

h_r = 3.42 (Emissivity = 1.0)

Use an emissivity of 0.736 for rusted black iron duct

$$h_r = (3.42)(0.736) = 2.52 \text{ Btu/hr-ft}^2\text{-°F}$$

(c) $$h_o = h_c + h_r$$

$$= 1.00 + 2.52 = 3.52 \text{ Btu/hr-ft}^2\text{-°F}$$

(d) Since t_w was assumed, it must be checked as shown:

$$t_w = t_m - \left(\frac{h_o}{h_o + h_{ic}}\right)(t_m - t_a)$$

$$t_m = \frac{2,000 + 225}{2} = 1,112°F$$

$$t_a = \frac{100 + 100}{2} = 100°F$$

$$t_w = 1,112 - \left(\frac{3.52}{3.52 + 2.62}\right)$$

$$(1,112 - 100) = 530°F$$

The assumed t_w was 525°F, which checks closely with 530°F

6. Determine the overall heat transfer coefficient (U_o) based on the outside surface area:

$$U_o = \frac{h_{io} h_o}{h_{io} + h_o} = \frac{(2.62)(3.52)}{(2.62) + (3.52)} = 1.50 \text{ Btu/hr-ft}^2\text{-°F}$$

7. Determine heat transfer area (A):

$$A = \frac{Q}{U_{od} \Delta t_m} = \frac{6,078,000}{(1.50)(653)} = 6,210 \text{ ft}^2$$

8. Determine length of duct (L) required:

$$L = \frac{6,210}{(2.224)(\pi)} = 886 \text{ ft}$$

The duct from the cupola to the vertical column is 60 feet long. The length of duct in the column section will, therefore, be 886 - 60 = 826 feet.

If columns are 50 feet high, then 826/50, or 16.5 columns will be required. Since the connecting ductwork between columns will consist of at least 2 feet of duct between each column, a total of 16 columns 50 feet high will be required.

Problem Note: The example illustrates one method of determining the length of duct needed to cool a given hot gaseous effluent. To determine the optimum duct diameter, it is necessary to make similar calculations for other duct diameters, and then determine the pressure drop through each system. By comparing the construction costs with the operating costs, the optimum duct diameter can be found.

Forced-Draft Cooling

Heat transfer by convection is due to fluid motion. Cold fluid adjacent to a hot surface receives heat, which is imparted to the bulk of the fluid by mixing. With natural convection, the heated fluid adjacent to the hot surface rises and is replaced by colder fluid. By agitating the fluid, mixing occurs at a much higher rate than with natural currents, and heat is taken away from the hot surface at a much higher rate. In most process applications, the agitation is induced by circulating the fluid at a rapid rate past the hot surface. This method of heat transfer is called forced convection. Since forced convection transfers heat much faster than natural convection, most process applications use forced-convection heat exchangers. Whenever possible, heat is exchanged between hot and cold streams to reduce the heat input to the process. There are, however, many industrial applications where it is not feasible to exchange heat, and so a cooling fluid such as water or air is used, and the heat removed from the stream is dissipated to the atmosphere. When water is used, the heat is taken from the process stream in a shell and tube cooler, and the heat picked up by the water is dissipated to the atmosphere in a cooling tower. When air is used as the cooling medium in either shell and tube or fin tube coolers, the heated air is discharged to the atmosphere and is not recirculated through the cooler.

With forced-convection cooling, the temperature of the cooled stream can be controlled within narrow limits even with widely varying atmospheric or water temperatures. Heat transfer area is greatly reduced from that needed with natural convection. Power requirements to force the process stream through the cooler are generally less. On the other hand, either a pump or a blower is needed to circulate the cooling fluid through the cooler. With water cooling, a cooling tower may be needed and additional maintenance is required to clean scale from the tubes.

FACTORS DETERMINING SELECTION OF COOLING DEVICE

Cooling by dilution air is commonly used where conveying air volumes are low or where there is a large volume of dilution inherent in the hoods required to capture the air contaminants. If large gas volumes are necessary, and dilution air is not economical, then direct cooling with water quench chambers is generally favored over other cooling devices. This is probably due to the small space requirements, ease of operation, and low installation costs of the water quench chambers. When the characteristics of the gaseous effluent and the contaminants are such that water cannot be used, natural convection-radiation cooling is generally employed. The ease of operation and low maintenance costs make these cooling systems more

attractive than forced-convection coolers. In fact, forced-convection equipment has seldom been used in air pollution control installations. In some cases it has been used where the heat of the cooling air can be utilized, for example as combustion air in the basic process being controlled.

CHAPTER 4

AIR POLLUTION CONTROL EQUIPMENT FOR PARTICULATE MATTER

INERTIAL SEPARATORS

HOWARD DEY, Air Pollution Engineer
JOHN MALONEY, Air Pollution Engineer*
JOSEPH D'IMPERIO, Air Pollution Engineer†

WET COLLECTION DEVICES

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

BAGHOUSES

HERBERT SIMON, Senior Air Pollution Engineer

SINGLE-STAGE ELECTRICAL PRECIPITATORS

HERBERT SIMON, Senior Air Pollution Engineer

TWO-STAGE ELECTRICAL PRECIPITATORS

ROBERT C. ADRIAN, Intermediate Air Pollution Engineer‡

OTHER PARTICULATE-COLLECTING DEVICES

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

*Now with the Air Pollution Control District of Riverside County, California.
†Now deceased.
‡Now with Aerojet-General Corporation, Azusa, California.

CHAPTER 4

AIR POLLUTION CONTROL EQUIPMENT FOR PARTICULATE MATTER

Air pollution control equipment may be classified into two groups: (1) Equipment controlling particulate matter, and (2) equipment controlling gaseous emissions. From an air pollution viewpoint, particulate matter is any material that exists as a solid or liquid at standard conditions. Some examples of particulates are smoke, dusts, fumes, mists, and sprays.

Devices for control of particulate matter are available in a wide variety of designs using various principles of operation and having a wide latitude in collection efficiency, initial cost, operating and maintenance costs, space, arrangement, and materials of construction. In selecting the optimum device for a specific job, it is necessary to consider many factors. Rose et al., (1958) consider the following factors significant:

1. Particulate characteristics, such as particle size range, particle shape, particle density, and physico-chemical properties such as agglomeration tendencies, corrosiveness, hygroscopic tendencies, stickiness, inflammability, toxicity, electrical conductivity, and so forth.

2. Carrier gas characteristics, such as temperature, pressure, humidity, density, viscosity, dew points of condensable components, electrical conductivity, corrosiveness, inflammability, toxicity, and so forth.

3. Process factors, such as volumetric gas rate, particulate concentration, variability of material flow rates, collection efficiency requirements, allowable pressure drop, product quality requirements, and so forth.

4. Operational factors, including structural limitations such as head room, floor space, and so forth, and equipment material limitations such as pressure, temperature, corrosion service requirements, and so forth.

In this chapter, devices for control of particulate matter have been grouped into six classes: (1) Inertial separators, (2) wet collection devices, (3) baghouses, (4) single-stage electrical precipitators, (5) two-stage electrical precipitators, and (6) other particulate-collecting devices.

INERTIAL SEPARATORS

Inertial separators are the most widely used devices for collecting medium- and coarse-sized particulates. The construction of inertial separators is usually relatively simple, and initial costs and maintenance costs are generally lower than for most other types of dust collectors. Collection efficiencies, however, are usually not high. Although suitable for medium-sized particulates (15 to 40 μ), ordinary inertial separators are generally unsuitable for fine dusts or metallurgical fumes. Dusts with a particle size ranging from 5 to 10 microns are normally too fine to be collected efficiently. In some cases, however, small-diameter, high-efficiency cyclones can be effective in collecting particles in the 5-micron range.

Inertial separators operate by the principle of imparting centrifugal force to the particle to be removed from the carrier gas stream. This force is produced by directing the gas in a circular path or effecting an abrupt change in direction.

SINGLE-CYCLONE SEPARATORS

A cyclone, which is an inertial separator without moving parts, separates particulate matter from a carrier gas by transforming the velocity of an inlet stream into a double vortex confined within the cyclone. In the double vortex the entering gas spirals downward at the outside and spirals upward at the inside of the cyclone outlet. The particulates, because of their inertia, tend to move toward the outside wall, from which they are led to a receiver.

Cyclones can be designed to handle a wider range of chemical and physical conditions of operation than most other types of collection equipment can handle. Any conditions for which structural materials are available can be met by a cyclone, if the degree of collection falls within the operating range of the cyclone, and physical characteristics of the particulates are such that no fouling of the cyclone or excessive wall buildup occurs.

Because of its versatility and low cost, the single-cyclone separator is probably the most widely used of the dry centrifugal separators. These cyclones are made in a wide variety of configurations. Although many design factors must be considered,

the degree of collection efficiency is most dependent upon the horsepower expended. Hence, cyclones with high inlet velocities, small diameters, and long cylinders are generally found most efficient. They are commonly called pencil cyclones or high-efficiency cyclones. Figure 44 shows a single high-efficiency cyclone, with typical dimension ratios as follows:

Major cylinder diameter	D_c
Major cylinder length	$L_c = 2\,D_c$
Cone length	$Z_c = 2\,D_c$
Gas outlet diameter	$D_e = \frac{D_c}{2}$
Gas outlet length	$H_c + S_c = 5/8\,D_c$
Gas inlet height	$H_c = \frac{D_c}{2}$
Gas inlet width	$B_c = \frac{D_c}{4}$
Dust outlet	$J_c = \frac{D_c}{4}$

In Figure 44, this cyclone consists of a cylinder with a tangential gas inlet, an axial gas outlet, and a conical lower section with an axial dust outlet. The gas inlet is a rectangular opening, with the height of the opening equal to twice the width. The gas outlet is a tube approximately one half the diameter of the major cylinder, concentric with and extending inside the major cylinder to slightly below the lower edge of the gas inlet. The tangential, high-velocity gas entry imparts a circular motion to the gas stream; the particulates, because of their greater inertia, tend to concentrate on the wall of the cyclone. The inlet gas follows a double vortex path, spiraling downward at the outside and spiraling upward at the inside to the gas outlet. Figure 45 illustrates the double-vortex path of the gas stream. The downward spiral, assisted by gravity, carries the particulates downward to the dust outlet where they drop into a dusttight bin, or are removed by a rotary valve or screw conveyor.

Theory of Operation

The centrifugal force applied to particulates varies as the square of the inlet velocity and inversely as the radius of the cyclone. These factors have been combined into a dimensionless quantity called the separation factor:

$$S = \frac{V^2}{rg} \qquad (42)$$

where

S = separation factor

V = inlet velocity, ft/sec

r = cyclone cylinder radius, ft

g = gravitational constant, 32.2 ft/sec^2.

It has not been possible to establish a definite correlation between separation factor and collection efficiency; yet, for cyclones of similar design and use, collection efficiency generally varies directly as a function of the separation factor.

Stern et al. (1956) discuss the variation of collection efficiency with inlet velocity. Several theoretical formulas are presented in which critical particle size is shown to vary as $1/V^{1/2}$. Critical particle size is defined as the largest sized particle not separated from the gas stream, all larger particles being separated, and critical-sized and all smaller sizes being lost into the outlet duct. The critical size varies inversely as the velocity, and the greater the critical size, the less efficient

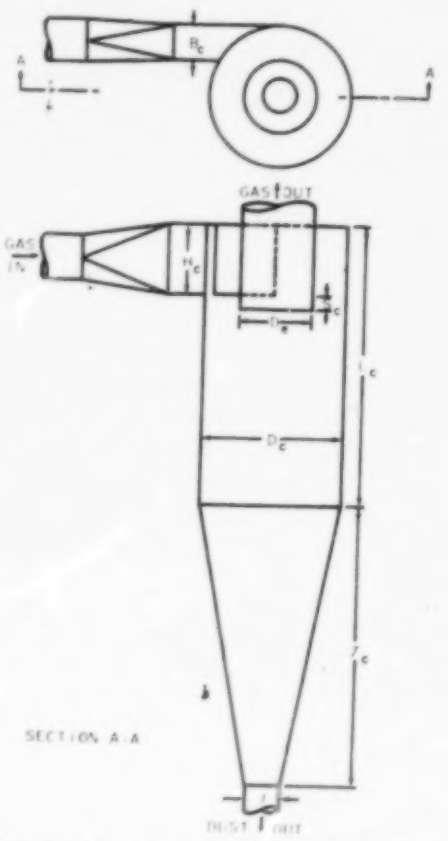


Figure 44. Single high-efficiency cyclone with typical dimension ratios.

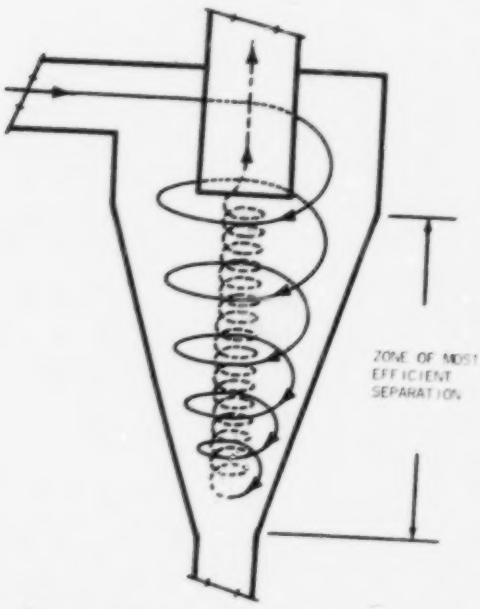


Figure 45. Double-vortex path of the gas stream in a cyclone (Montross, 1953).

is the cyclone collection. The collection efficiency, therefore, varies as the inlet velocity. There are, however, limits to the inlet velocity; if it is too great, turbulence develops to such a degree at the inlet that overall cyclone efficiency is reduced. The velocity at which excessive turbulence occurs is dependent upon configuration of the inlet, design of the cyclone, and the characteristics of the carrier gas.

Separation Efficiency

For high efficiency, the separating forces should be large and the dust removal effective so that separated dust is not reentrained. In general, cyclone efficiency increases with an increase in the following: (1) Density of the particulate matter, (2) inlet velocity into the cyclone, (3) cyclone body length, (4) number of gas revolutions (experiments indicate that the number of revolutions made by the gas stream in a typical simple cyclone ranges from 0.5 to 3 and averages 1.5 for cyclones of normal configuration), (5) ratio of cyclone body diameter to cyclone outlet diameter, (6) particle diameter, (7) amount of dust entrained in carrier gas, and (8) smoothness of inner cyclone wall.

An increase in the following will decrease the overall efficiency: (1) Carrier gas viscosity, (2) cyclone diameter, (3) gas outlet diameter, (4) gas inlet duct width, (5) inlet area, and (6) gas density.

A common cause of poor cyclone performance is leakage of air into the dust outlet. A small air leak at this point can result in an appreciable decrease in collection efficiency, particularly with fine dusts.

For continuous withdrawal of collected dust a rotary star valve, a double-lock valve, or a screw conveyor with a spring-loaded choke should be used.

Collection efficiency is noticeably reduced by the installation of inlet vanes, probably because of interference with the normal flow pattern. In general, all sorts of guide vanes, straightening vanes, baffles, and so forth placed inside an otherwise well-designed cyclone have been found of little value or actually detrimental. In some instances, for poorly designed cyclones, these devices have improved performance. Baffles designed to reduce leakage of air into the dust outlet are sometimes helpful. These consist of a horizontal, circular device installed on the cyclone axis near the dust outlet.

In practice, extensive agglomeration may be expected for dust concentrations greater than 100 grains per cubic foot and may be present at much smaller concentrations, depending upon the physical properties of the particulates being collected. Fibrous or tacky particles are especially apt to agglomerate. Agglomeration produces a larger effective particle size and thereby increases the efficiency of separation. Nevertheless, extremely sticky, hygroscopic, or similar material that could possibly plug the dust outlet or accumulate on the cyclone walls adversely affect cyclone operation. In addition, the agglomeration effect is reduced sharply when high inlet velocities are used. In some cases where agglomeration was significant, an increase in cyclone inlet velocity actually reduced the collection efficiency. Conversely, the efficiency was improved by reducing the inlet velocity.

Pressure Drop

A satisfactory method of determining the pressure drop of a given cyclone has not yet been developed. Pressure drop, to be determined accurately, should be determined experimentally on a geometrically similar prototype. Lapple (1963) has suggested a relationship that may be used to approximate the pressure drop:

$$F = \frac{KBH}{D^2} \qquad (43)$$

where

- F = cyclone friction loss, number of cyclone inlet velocity heads, dimensionless
- K = empirical proportionality constant, dimensionless
- B = width of rectangular cyclone inlet duct, ft
- H = height of rectangular cyclone inlet, ft
- D = cyclone gas exit duct diameter, ft.

In this equation, K varies from 7.5 to 18.4. Pressure drop values, for a value of K = 13.0, have been found to check with experimental data within 30 percent.

The Industrial Hygiene Codes Committee (1938) states that the resistance pressure across pull-through cyclones is approximately three inlet velocity heads. For pushthrough cyclones venting directly to the atmosphere, the resistance pressure is approximately one and one-half velocity heads. These values are valid for simple cyclones, but a considerable variation may be expected for cyclones of unusual design.

OTHER TYPES OF CYCLONE SEPARATORS

High-Efficiency Cyclone Separators

When collection of particulates in the 5- to 10-micron range is desired, long, small-diameter, high-efficiency cyclones may sometimes be used. Operation is, however, more expensive, since pressure drop increases with a decrease in cyclone diameter; the greater the pressure drop, the greater the power cost.

High-efficiency cyclones are made more effective than simple cyclones by increasing the body length and decreasing the diameter. These two alterations act both to increase retention time in the cyclone and exert greater centrifugal force on the particulates, which results in greater separation.

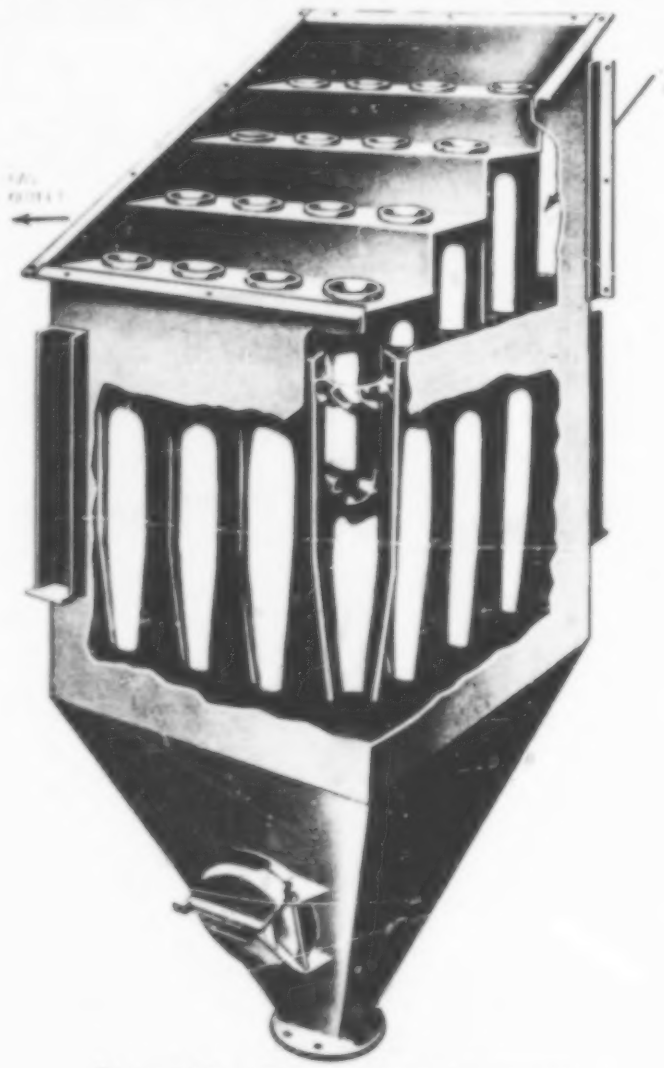


Figure 46. Multiple-cyclone separator (Western Precipitation Division of Joy Manufacturing Company, Los Angeles, Calif.).

Multiple-Cyclone Separators

A multiple-cyclone separator consists of a number of small-diameter cyclones operating in parallel, having a common gas inlet and outlet, as shown in Figure 46. The flow pattern differs from that in a conventional cyclone in that the gas, instead of entering at the side to initiate the swirling action, enters at the top of the collecting tube and has a swirling action imparted to it by a stationary vane positioned in its path. The diameters of the collecting tubes usually range from 1 foot to as small as 2 inches. Properly designed units can be constructed that have a collection efficiency as high as 90 percent for particulates in the 5- to 10-micron range.

Mechanical, Centrifugal Separators

Several types of collectors are readily available in which centrifugal force is supplied by a rotating vane. Figure 47 illustrates this type of collector, in which the unit serves both as exhaust fan and dust collector. In operation, the rotating fan blade exerts a large centrifugal force on the particulates, ejecting them from the tip of the blades to a skimmer bypass leading into a dust hopper.

Efficiencies of mechanical, centrifugal separators are somewhat higher than those obtainable with simple cyclones. Mechanical, centrifugal separators are compact and are particularly useful where a large number of individual collectors are required. These units cannot, however, be generally used to collect particulates that cake or tend to accumulate on the rotor blades since these particulates cause clogging and unbalancing of the impellor blades with resultant high maintenance costs and shutdowns.

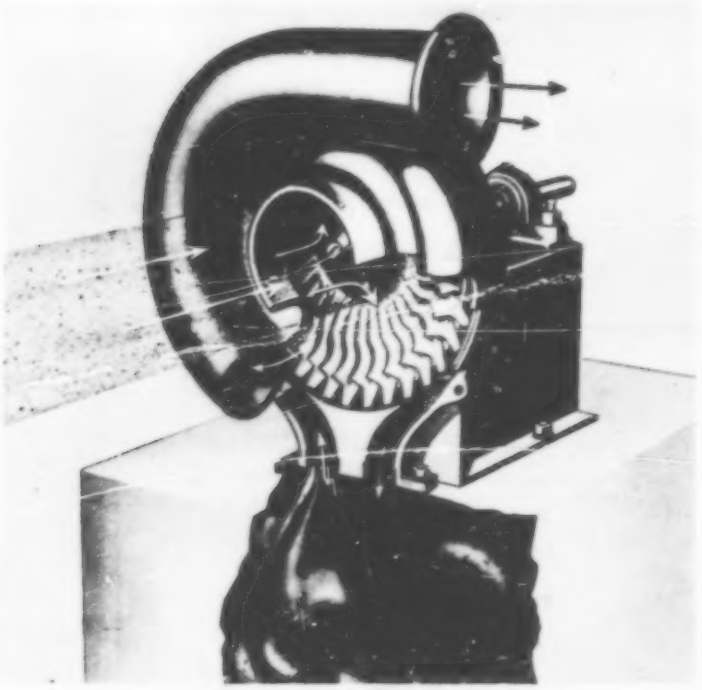


Figure 47. Mechanical, centrifugal separator (American Air Filter Company, Inc., Louisville, Kentucky).

PREDICTING EFFICIENCY OF CYCLONES

Many investigations attempt to correlate cyclone performance with various parameters. Lapple (1951, 1963) treats the subject at length in several publications, introducing the concept of cut size (D_{pc}), which is defined as the diameter of those particles collected with 50 percent efficiency. Collection efficiency for particles larger than the cut size will be greater than 50 percent while that for smaller particles will be less. Another term used is the average particle size (D_p), which is simply the average of the size range. For example, if the size range is 10 to 15 microns, D_p = 12.5 microns.

A separation efficiency correlation for typical cyclones of the type mentioned by Lapple is presented in Figure 48. Additional experimental data have been used to check Lapple's ratios of D_p/D_{pc}. All results compared favorably with the original curve of Lapple. Manufacturers' efficiency curves for cyclones and multiple cyclones converted to D_p/D_{pc} curves had slightly lower efficiencies than Lapple's correlation for D_p/D_{pc} ratios greater than 1. The maximum deviation noted was 5 percent for the cyclone curve at D_p/D_{pc} of 1-1/2 and 12 percent for the multiple-cyclone curve at D_p/D_{pc} of 2 to 3. Apparently, Lapple's correlation is sufficiently accurate for an engineering estimation of many cyclone applications. A size-efficiency curve may be calculated from this correlation after the actual size of the cut size particle is established. Particle cut size may be calculated by equation 44:

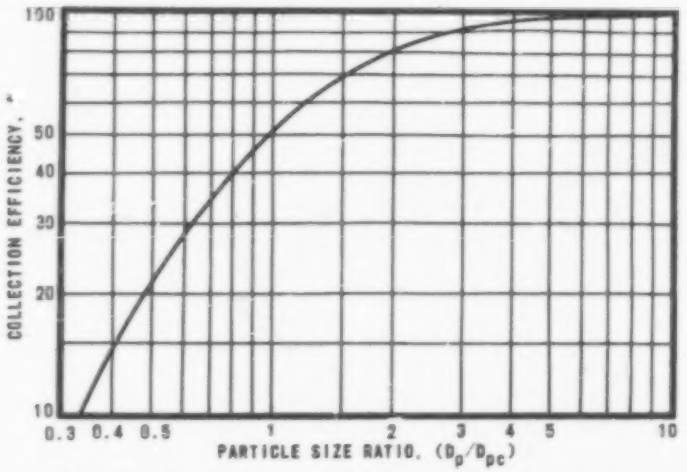


Figure 48. Cyclone efficiency versus particle size ratio (Lapple, 1951).

$$D_{pc} = \sqrt{\frac{9\mu b}{2 N_e V_i (\rho_p - \rho_g) \pi}} \qquad (44)$$

where

D_{pc} = diameter cut size particle collected at 50 percent efficiency, ft

μ = gas viscosity, lb mass/sec-ft = centipoise x 0.672×10^{-3}

b = cyclone inlet width, ft

N_e = effective number of turns within cyclone. The number of turns are about five for a high-efficiency cyclone but may vary from 1/2 to 10 for other cyclones (Freidlander et al., 1952)

V_i = inlet gas velocity, ft/sec

ρ_p = true particle density, lb/ft^3

ρ_g = gas density, lb/ft^3.

Figure 49 presents a graphical solution of this equation for typical cyclones having an inlet velocity of 50 fps, gas viscosity of 0.02 centipoise, effective number of turns equal to five, and cyclone inlet width of $D_c/4$. From these curves, the cut size may be approximated from the cyclone diameter and the dust's true specific gravity. Corrections for viscosity, inlet gas velocity, effective number of turns, and inlet width different from those assumed in Figure 49 may be found graphically by using Figure 50.

The calculated particle cut size may be used in conjunction with the general cyclone efficiency curve of Lapple (1951, 1963) as shown in Figure 48 to calculate a particle size efficiency curve for the cyclone in question. A particle size distribution of the feed must also be known or calculable to continue the final efficiency determina-

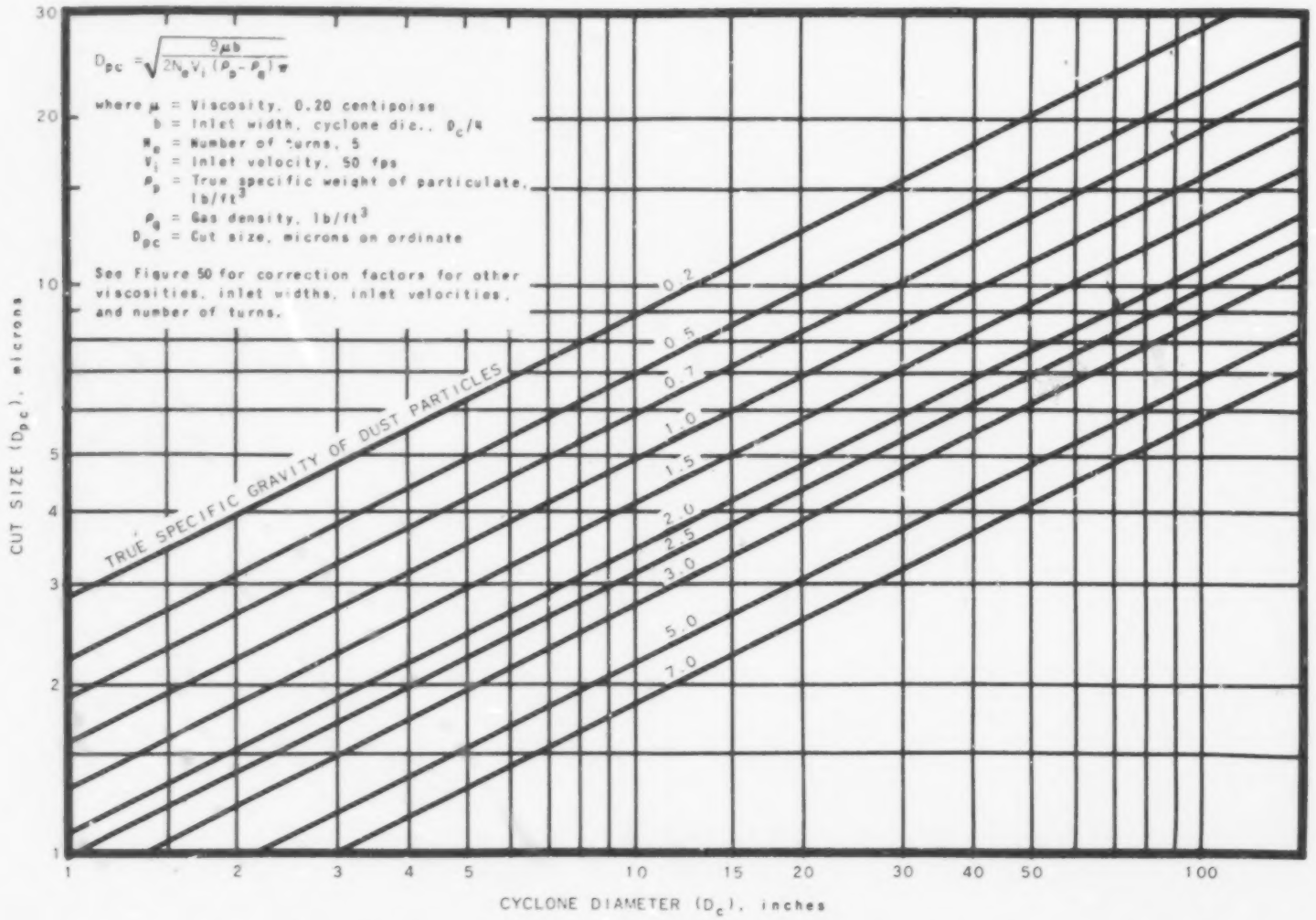


Figure 49. Cyclone diameter versus cut size (Lapple, 1951).

tion. Size distribution data should be plotted on logarithmic-probability paper to check for reliability. Drinker and Hatch (1954) state that Epstein's work shows this plot is a straight line for operations such as crushing and grinding. An investigation of test results on samples from crystallization, spray drying, calcining, and other physical and chemical processes indicates that the particle size distribution of these processes usually follows the laws of probability, and plots as a straight line on logarithmic-probability paper. The actual distribution used in the calculations should be taken from the straight-line "smoothed data." Methods of determining particle sizes have an effect in determining the straight-line plot. Most data from screen analyses plot as a curve on logarithmic-probability paper if the values for screens smaller than 150-mesh Tyler or 140-mesh U. S. Screen Scale are used. Specifically, minus 200 mesh and minus 325 mesh (both sometimes reported in screen analyses) give points that are usually not in agreement with data obtained when the minus-100-mesh material is subjected to micromeragraph analysis.

A fractional-efficiency curve for a geometrically similar cyclone may be constructed from a given fractional-efficiency curve by the following procedure:

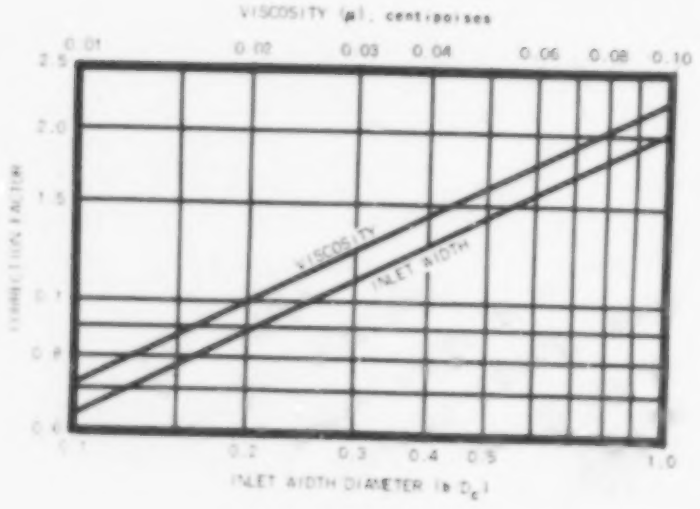
1. Determine D_{pc} from the fractional-efficiency curve for a known cyclone.

2. Replot the fractional-efficiency curve as efficiency versus the ratio D_p/D_{pc}.

3. Calculate D_{pc} for the unknown cyclone from equation 44 or Figures 49 and 50.

4. Assume efficiency versus D_p/D_{pc} curve applies to the unknown cyclone.

   Using the value of D_{pc} for the unknown cyclone, and the efficiency versus D_p/D_{pc} curve, calculate new values of D_p versus efficiency and plot as the fractional-efficiency curve of the unknown cyclone.



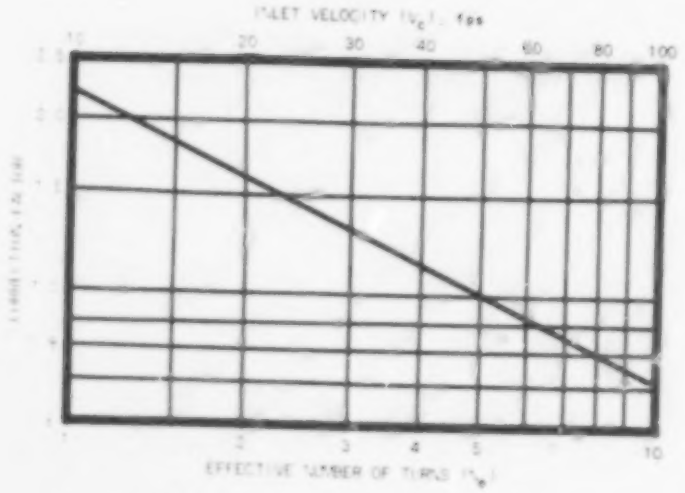


Figure 50. Correction factors for Figure 49 (Lapple, 1951).

5. In most cases, a range of D_{pc} for the unknown cyclone should be selected instead of a single value. Then, using the maximum and minimum values for D_{pc}, plot two size efficiency curves. The overall efficiencies obtained from these curves serve as an engineering estimate of the expected cyclone performance.

In some cases, size data are available only on the materials already collected in a cyclone separator, with no data on the cyclone loss rate and size distribution. The calculation procedure is identical to the normal method except for the final loss rate step. Here a loss factor must be determined from the size range efficiency. If the efficiency is 50 percent, the loss factor is 1, and the cyclone loses 1 pound of material for every pound collected in this size range. If the efficiency is 75 percent, the loss rate is 1/3, and similarly, if the efficiency is 25 percent, the loss rate is 3. The loss rate for each particle size range is the quantity collected multiplied by the loss factor.

An alternative method of obtaining total weight of the fraction charged to the cyclone consists of dividing each weight fraction by the fractional efficiency. The weight loss is then the difference between the amount collected and the feed calculated from the efficiency.

The previously discussed method of predicting cyclone collection efficiencies is, of course, only approximate. It can be useful if applied correctly. Its utility will be increased once additional test information is obtained on various cyclones. As more information is obtained, a family of curves can be developed for various types of cyclones. The resulting data should be similar to the data herein, and the use of the illustrated curves could be extended to many different cyclone designs without appreciable error.

Method of Solving a Problem

Knowing the cyclone dimensions, the inlet gas velocity, the viscosity, and the particle size distribution of the dust, predict cyclone efficiencies as shown in example 18.

Example 18

Given:

Cyclone diameter,	D_c	=	72 in.
Inlet width,	bc	=	17 in. = 0.235 D_c
Inlet velocity,	V_c	=	2,400 fpm = 40 fps
Specific gravity		=	1.5
Gas viscosity		=	0.0185 centipoise

Particle size distribution of dust entering the cyclone (See curve in Figure 51).

Problem:

Determine the particle cut size D_{pc} and use these data to determine expected cyclone performance.

Solution:

1. Determine the particle cut size:

   From Figure 49, the uncorrected D_{pc} = 10.5 microns.

   The following correction factors are shown by calculation and can also be obtained from Figure 50:

   Inlet width factor = $\sqrt{\frac{0.235}{0.250}}$ = 0.97

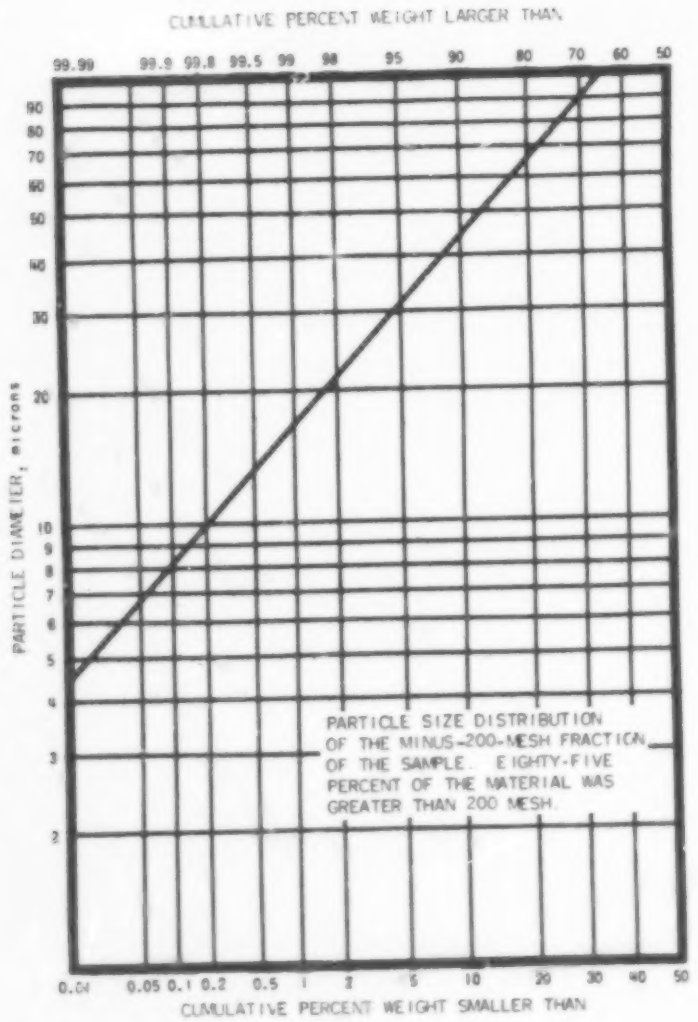


Figure 51. Particle size distribution of dust in example problem.

$$\text{Velocity factor} = \sqrt{\frac{50}{40}} = 1.12$$

$$\text{Viscosity factor} = \sqrt{\frac{0.022}{0.020}} = 0.96$$

Number of turns factor = 1.0 (Number of turns assumed to be 5)

Corrected cut size = (D_{pc})(correction factors)

= (10.5)(0.97)(1.12)(0.96)(1.0)
= 11.0 microns.

2. Calculate collection efficiencies by size increments:

   Select size increments to obtain several values of D_p less than D_{pc}, and five or more values between D_p/D_{pc} ratios of 1 to 10. Calculate the average size of each increment and tabulate as D_p. Calculate the ratio D_p/D_{pc} and tabulate for the range at D_p. Particles of such size that the ratio D_p/D_{pc} is greater than 10 are considered to be collected at 100 percent efficiency. From Figure 48 obtain the collection efficiencies for the size increments represented by the D_p/D_{pc} ratios and tabulate (Table 29).

Table 29. COLLECTION EFFICIENCIES FOR SIZE INCREMENTS

Particle size, microns		Ratio	Efficiency
Range	Avg D_p	D_p/D_{pc}	% by wt
0 to 2	1	0.09	1
2 to 4	3	0.27	7
4 to 6	5	0.45	17
6 to 8	7	0.64	29
8 to 10	9	0.82	40
10 to 12	11	1.00	50
12 to 15	13.5	1.23	60
15 to 20	17.5	1.59	72
20 to 30	25	2.28	84
30 to 40	35	3.18	91
40 to 50	45	4.1	95
50 to 60	55	5.0	96
60 to 70	65	5.9	97
70 to 80	75	6.8	98
80 to 90	85	7.7	98.5
90 to 100	95	8.6	99
100+	100+	10+	100

3. Plot the given particle size data of the inlet dust to the cyclone:

   Plot the particle size data on logarithmic-probability paper and draw the best straight line, giving maximum consideration to the data that lie between 20 to 80 percent of the extreme upper and lower values of the particle size range (Drinker and Hatch, 1954).

4. Tabulate the weight percentage of the dust corresponding to the micron size increments:

   Using the smoothed data, as shown above, tabulate the weight percentages corresponding to the size increments in microns (Table 30).

5. Determine the overall efficiency:

   When the particle size distribution is for the cyclone feed, as given in this example, multiply the percentage for each size increment by its collection efficiency. The sum of these products is the overall efficiency. This calculation is presented in Table 31.

6. In some existing installations, it may be difficult or impossible to determine the particle size analysis of the dust to the cyclone. In

Table 30. WEIGHT PERCENTAGES PER SIZE INCREMENTS

Particle size, microns Range	Avg D_p	Wt % for size
0 to 2	1	
2 to 4	3	0.01
4 to 6	5	0.02
6 to 8	7	0.06
8 to 10	9	0.11
10 to 12	11	0.15
12 to 15	14	0.35
15 to 20	18	0.90
20 to 30	25	2.80
30 to 40	35	3.60
40 to 50	45	4.50
50 to 60	55	4.50
60 to 70	65	5.00
70 to 80	75	4.00
80 to 90	85	4.00
90 to 100	95	5.00
100+	100+	65.00

Table 31. CALCULATION OF OVERALL EFFICIENCY

Particle size, microns Range	Avg D_p	Efficiency, % by wt	% by wt x efficiency
0 to 2	1	< 1	
2 to 4	3	7	0.001
4 to 6	5	17	0.003
6 to 8	7	29	0.017
8 to 10	9	40	0.044
10 to 12	11	50	0.075
12 to 15	14	60	0.210
15 to 20	18	72	0.648
20 to 30	25	84	2.35
30 to 40	35	91	3.28
40 to 50	45	95	4.28
50 to 60	55	96	4.32
60 to 70	65	97	4.85
70 to 80	75	98	3.92
80 to 90	85	98.5	3.94
90 to 100	95	99	4.95
100+	100+	100	65.00
Total			97.89
Loss			2.11
Overall efficiency			97.89
Loss, % of feed			2.11

these cases, a particle size analysis of the percentage for each size increment should be divided by its collection efficiency. The sum of the quotients gives the cyclone feed expressed as percent of the cyclone catch. Divide 100 by the cyclone catch to obtain the overall efficiency. These calculations are presented in Table 32, with the particle size distribution curve for this problem, but it is assumed that these data are the particle size distribution curve for the cyclone catch.

Table 32. CALCULATION OF OVERALL EFFICIENCY FOR SPECIAL CASES

Particle size, microns Range	Avg D_p	% by wt efficiency	% by wt x efficiency
0 to 2	1	< 1	
2 to 4	3	7	0.14
4 to 6	5	17	0.11
6 to 8	7	29	0.20
8 to 10	9	40	0.27
10 to 12	11	50	0.30
12 to 15	14	60	0.58
15 to 20	18	72	1.25
20 to 30	25	84	3.33
30 to 40	35	91	3.96
40 to 50	45	95	4.74
50 to 60	55	96	4.69
60 to 70	65	97	5.15
70 to 80	75	98	4.08
80 to 90	85	98.5	4.06
90 to 100	95	99	5.05
100+	100+	100	65.00
Total			102.91
Loss			2.91
Overall efficiency			97.16
Loss, % of feed			2.84

From the preceding problem, the cyclone loss expressed as percent of feed is obviously 100 minus the overall efficiency as calculated. If the loss of any incremental size fraction is desired, this may be calculated as follows:

1. Calculate the weight of each incremental fraction of feed by using particle size distribution data and total feed weight.

2. Multiply this weight by the percentage loss (100 minus the efficiency) for each increment to determine the weight loss.

WET COLLECTION DEVICES

Wet collection devices use a variety of methods to wet the contaminant particles in order to remove them from the gas stream. There is also a wide

range in their cost, their collection efficiency, and the amount of power they expend.

Wet collectors have the following advantages: They have a constant pressure drop (at constant volume), they present no secondary dust problem in disposing of the collected dust, and they can handle high-temperature or moisture-laden gases. They can also handle corrosive gases or aerosols, but corrosion-resistant construction may add materially to their cost. Space requirements are reasonably small. Disposal of the waste water or its clarification for reuse may, however, be difficult or expensive.

Their collection efficiency varies widely with different designs. Most collectors decline rapidly in efficiency for particles between 1 and 10 microns. Many investigators believe that collection efficiency is directly related to the total power expended in forcing the gases through the collector and in generating the water spray.

The process of contacting an air-contaminated gas with a scrubbing liquid results in dissipation of mechanical energy in fluid turbulence and, ultimately, in heat. The power dissipated is termed the contacting power. Semrau (1960) made an exhaustive literature survey to correlate scrubber efficiency with contacting power. He states that contacting power can be derived from (1) the kinetic energy or pressure head of the gas stream, (2) the kinetic energy or pressure head of the liquid, or (3) energy supplied mechanically by a rotor. He concludes: "Efficiency is found to have little relation to scrubber design and geometry, but to be dependent on the properties of the aerosol and on the contacting power."

THEORY OF COLLECTION

The principal mechanisms by which liquids may be used to remove aerosols from gas streams are as follows:

1. Wetting of the particles by contact with a liquid droplet,

2. impingement of wetted or unwetted particles on collecting surfaces followed by their removal from the surfaces by a flush with a liquid.

MECHANISMS FOR WETTING THE PARTICLE

The particles can be wetted by the following mechanisms:

1. Impingement by spray droplets. A spray directed across the path of the dust particles impinges upon them with an efficiency proportional to the number of droplets and to the force imparted to them. Johnstone and Roberts (1949) states that the optimum droplet particle size is about 100 microns. Above 100 microns there are too few droplets, and below 100 microns, the droplets do not have sufficient force. Fine spray is effective by another mechanism, diffusion.

2. Diffusion. When liquid droplets are dispersed among dust particles, the dust particles are deposited on the droplets by Brownian movement or diffusion. This is the principal mechanism in the collection of submicron particles. Diffusion as the result of fluid turbulence may also be an appreciable mechanism in the deposition of dust particles on spray droplets.

3. Condensation (Lapple, 1963). If a gas is cooled below the dewpoint in passing through a wet collector, then condensation of moisture occurs, the dust particles acting as condensation nuclei. This effective increase in the particle size makes subsequent collection easier. Condensation is an important mechanism only for gases that are initially hot. Condensation alone can remove only relatively small amounts of dust, since the amount of condensation required to remove large concentrations is greater than can be achieved.

4. Humidification and electrostatic precipitation have been suggested as mechanisms that facilitate collection of particles by causing them to agglomerate. These effects are not, however, well understood and cannot be relied upon to play any significant role in the collection mechanisms.

Several investigators have used wetting agents for scrubbing water in an effort to improve collection efficiency. In most cases, little or no improvement has been found (Friedlander et al., 1952). In order to be wetted, a particle must either make contact with a spray droplet or impinge upon a wetted surface. When either of these occurs, the particle is apparently wetted as adequately without the use of wetting agents as it is with their use.

Particles that have been wetted must reach a collection surface if the collecting process is to be completed. They may be impinged against surfaces placed in the path of the gas flow; or centrifugal action may be used to throw them to the outer walls of the collector; or simple gravity settling may be employed.

In some devices impingement is the principal collection mechanism, the water sprays being

used merely to remove the dust from the collection surfaces.

Centrifugal action may be provided by a vessel that is essentially the same as a dry cyclone separator. Helical vanes in a cylindrical vessel are extensively used to supply centrifugal action. In some devices, baffles are shaped and placed so that they act both as impingement and collection surfaces, and as imparters of cyclonic motion to the gas stream.

TYPES OF WET COLLECTION DEVICES

Spray Chambers

The simplest type of scrubber is a chamber in which spray nozzles are placed. The gas stream velocity decreases as it enters the chamber, and the wetted particles settle and are collected at the bottom of the chamber. The outlet of the chamber is sometimes equipped with eliminator plates to help prevent the liquid from being discharged with the clean air stream. The spray chamber is extensively used as a gas cooler. Its efficiency as a dust collector is low except for coarse dust. Efficiency can be improved by baffle plates upon which particles can be impinged. Water rates range from 3 to 8 gallons per minute (gpm) per 1,000 cfm. Installed costs range from $0.25 to $0.50 per cfm.

Cyclone-Type Scrubbers

Cyclone-type scrubbers range from simple dry cyclones with spray nozzles to specially constructed multistage devices. All feature a tangential inlet to a cylindrical body, and many feature additional vanes that accentuate the cyclonic action and also act as impingement and collection surfaces.

Figure 52 shows how a dry cyclone can be converted to a scrubber. Some investigators disagree on the most effective placement of spray nozzles; however, the principal benefit is derived from the wetted walls in preventing reentrainment of separated material. Figure 53 shows a standard type of cyclone scrubber. The gas enters tangentially at the bottom of the scrubber and pursues a spiral path upwards. Liquid spray is introduced into the rotating gas from an axially located manifold in the lower part of the unit. The atomized fine-spray droplets are caught in the rotating gas stream, and are, by centrifugal force, swept across to the walls of the cylinder, colliding with, absorbing, and collecting the dust or fume particles en route. The scrubbing liquid and particles run down the walls and out of the bottom of the unit; the clean gas

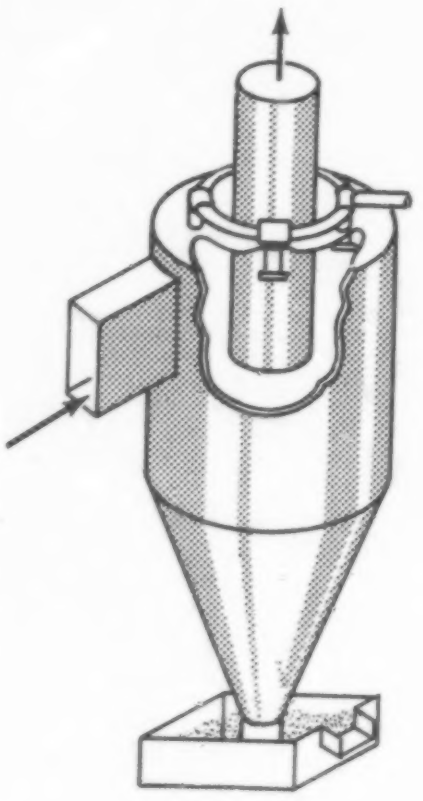


Figure 52. Conventional cyclone converted to a scrubber.

leaves through the top. The scrubber in Figure 54 uses helical baffles to provide prolonged centrifugal action, and multiple spray nozzles to increase spray contact time.

Since centrifugal force is the principal collecting mechanism, efficiency is promoted by comparatively high gas velocities. Pressure drop varies from 2 to 8 inches water gage, and water rates vary from 4 to 10 gpm per 1,000 cfm gas handled. The purchase cost for completed units varies from $0.50 to $1.50 per cfm gas handled for standard construction. If corrosion-resistant materials are required, costs may be much higher.

Orifice-Type Scrubbers

Orifice-type scrubbers are devices in which the velocity of the air is used to provide liquid contact. The flow of air through a restricted passage (usually curved) partially filled with water causes the dispersion of the water. In turn, centrifugal forces, impingement, and turbulence cause wetting of the particles and their collection. Water quantities in motion are relatively large, but most of the water can be recirculated without pumps or spray nozzles. Recirculation rates are as high as 20 gpm per 1,000 cfm gas. The degree of dispersion of the water is, however, not as great as is attained with spray nozzles. Pressure drop and purchase costs are comparable

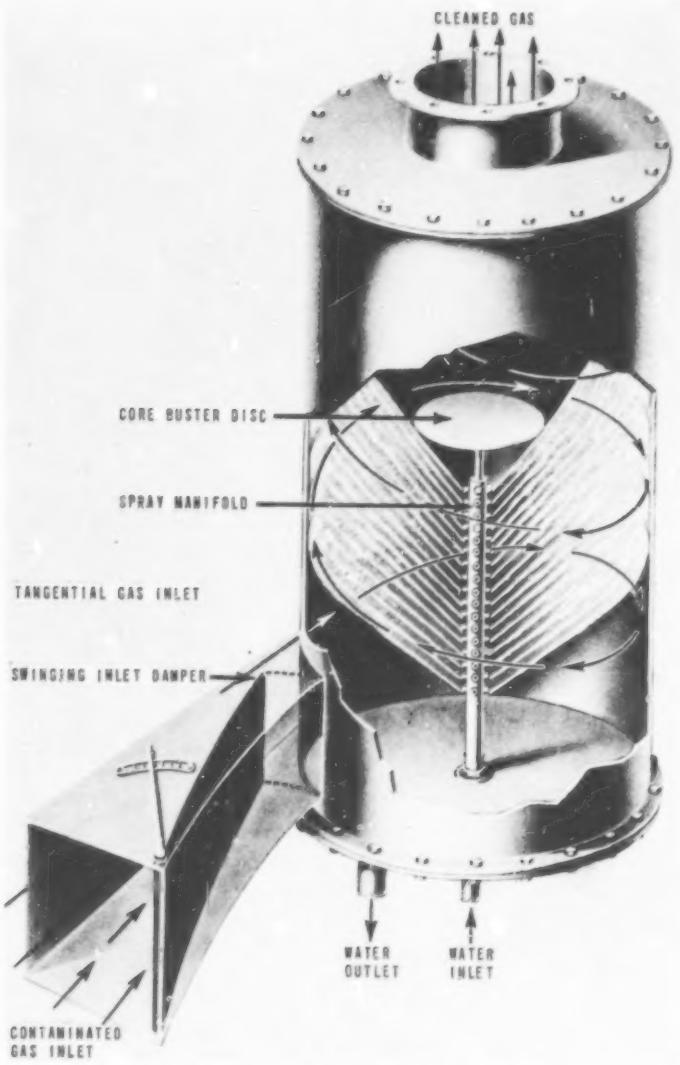


Figure 53. Cyclone scrubber (Chemical Construction Co., New York, N. Y.).

to those for cyclone-type scrubbers. Figure 55 illustrates the action in an orifice-type scrubber. Zig-zag plates remove spray droplets at the gas exit. Figure 56 illustrates a type in which the orifice is formed by a cone inside the entrance ducts. Baffle plates remove spray droplets at the gas exit.

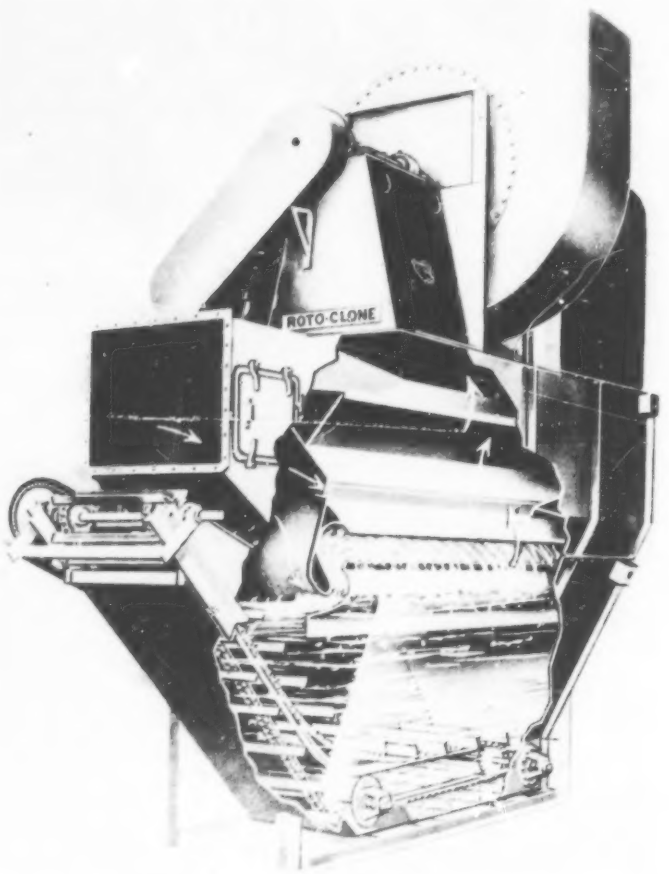


Figure 55. Orifice scrubber (American Air Filter Co., Inc., Louisville, Ky.).

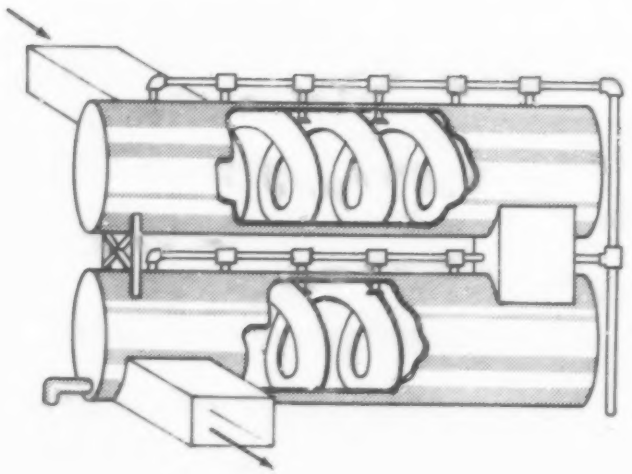


Figure 54. Double-chamber cyclone scrubber with helical baffles.

Mechanical Scrubbers

Mechanical scrubbers include those devices in which the water spray is generated by a rotating element such as a drum or disk. As with the orifice types, the water is usually recirculated. In the scrubber in Figure 57, the spray, because it is generated in a restricted passage, promotes extreme turbulence and increases chances for collision between dust particles and spray droplets. Recirculation rates and degree of dispersion vary widely with the different types of rotating elements. Installed costs are around $1.00 per cfm gas for standard construction.

Mechanical, Centrifugal Collector With Water Sprays

A spray of water added to the inlet of a mechanical, centrifugal collector increases its collection efficien-

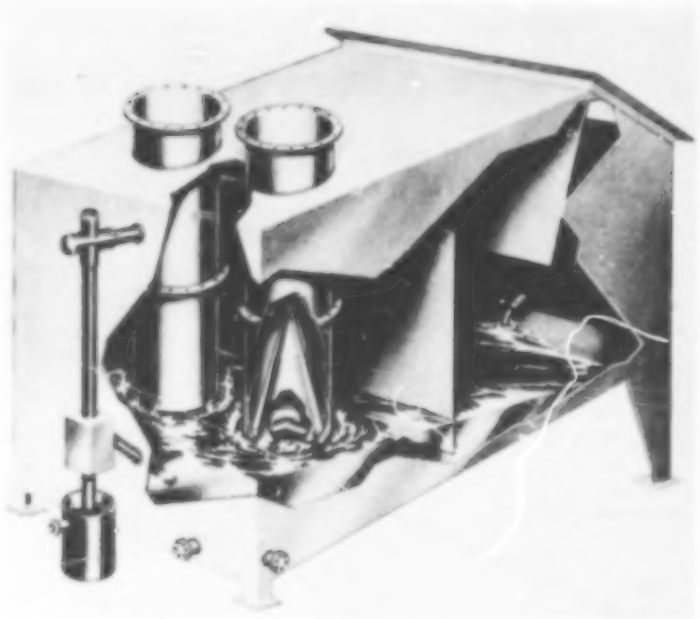


Figure 56. Orifice scrubber (Western Precipitation, Division of Joy Manufacturing Company, Los Angeles, California).

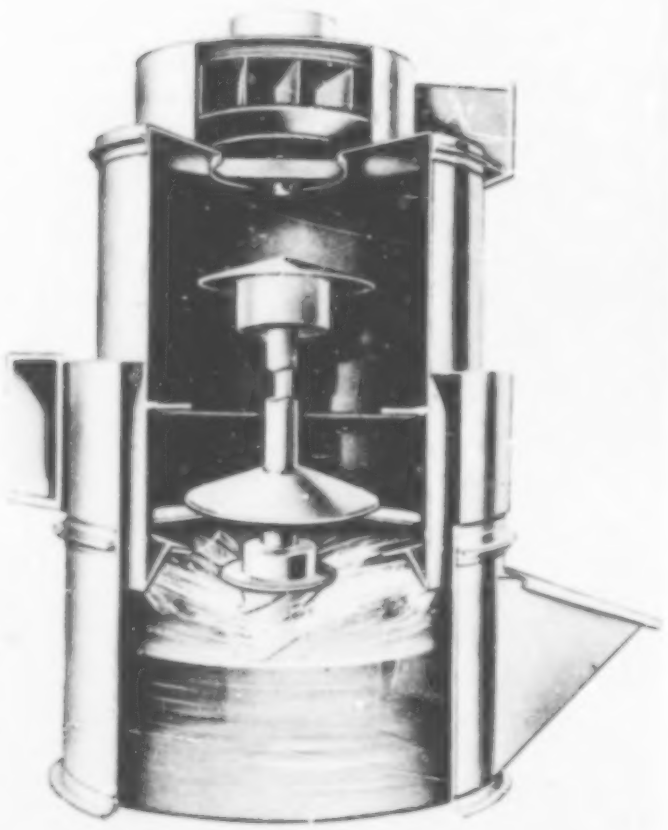


Figure 57. Mechanical scrubber (Schmieg Industries, Division of Aero-Flow Dynamics, Inc., Detroit, Michigan).

cy. The mechanism is mainly one of impingement of dust particles on the rotating blades. The spray formed merely keeps the blades wet and flushes away the collected dust (Figure 58). By the same mechanism, good collection efficiencies can be achieved by injecting a spray of water into the inlet of an ordinary paddle-type centrifugal fan. This can substantially increase the collection efficiency of a scrubbing installation. It also increases, however, the wear and corrosion rate of the fan. Installed costs for mechanical, centrifugal types are approximately $1.00 per cfm gas.

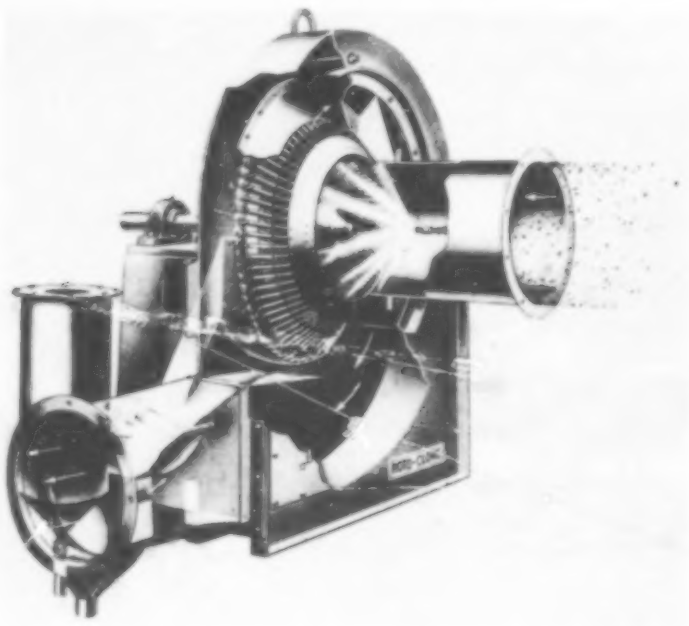


Figure 58. Mechanical, centrifugal scrubber (American Air Filter Co., Inc., Louisville, Ky.).

High-Pressure Sprays

Most scrubbers operate with water pressure of from 100 to 150 psi. Increasing the pressure at the spray nozzles has been found to increase collection efficiency by creating more droplets and giving them more force. A number of scrubbers are now designed, therefore, to operate with water pressures at the spray nozzles of from 300 to 600 psi. Very small nozzle orifices are used, and in most cases this precludes recirculation of water. Nozzles must be located so that collision between water droplets is minimized, and the design must ensure maximum collision between water droplets and the dust particles. Very high collection efficiencies have been reported. Water consumption ranges from 5 to 10 gallons per 1,000 cfm. Installed costs are about the same as those for cyclone scrubbers. For a given water rate, operating costs are greater, but collection efficiencies are higher.

Venturi Scrubbers

In the venturi scrubber, the gases are passed through a venturi tube to which low-pressure water is added at the throat. Gas velocities at the throat are from 15,000 to 20,000 fpm, and pressure drops are from 10 to 30 incnes water gage. Recirculation of water is feasible. The predominating mechanism is believed to be impaction. In spite of the relatively short contact time, the extreme turbulence in the venturi promotes very intimate contact. The wetted particles and droplets are collected in a cyclone spray separator, as shown in Figure 59. Water rates are about 3 gpm per 1,000 cfm gas. Very high collection efficiencies have been reported for very fine dusts. Costs are from $0.50 to $2.00 per cfm for mild steel construction and $1.00 to $3.00 per cfm for stainless steel.

Packed Towers

In packed towers the contaminant-laden stream is passed through a bed of a granular or fibrous collection material, and a liquid is passed over the collecting surface to keep it clean and prevent reentrainment of deposited particles. Collection of the contaminant depends upon the length of contact time of the gas stream on the collecting surfaces. This collecting surface material should have a relatively large surface area, low weight per unit volume, and large free cross-section. Irregularly shaped ceramic saddles are commonly used as packing. Coke, broken rock, stoneware shapes, Raschig rings, and spiral-shaped rings are other materials and shapes often used. Bed depths may vary from a fraction of an inch to several feet depending upon the type of packing and the application. Coarsely packed beds are used for removing coarse dusts and mists that are 10 microns or larger; velocities through the bed should be about 400 fpm. Finely packed beds may be used for removing contaminants in the 1- to 5-micron range, but the velocity through the bed must be kept very low, preferably below 50 fpm. Finely packed beds tend to clog; their applications are generally limited to dust-laden gases with relatively low grain loadings or to liquid entrainment collection.

Both costs and collection efficiency vary widely with bed depths, design velocities, and types of packing. For comparatively shallow beds, high velocity, and coarse packing, the costs and collection efficiency are comparable to those for a simple spray chamber. For deep beds, fine packing, and low velocities, both the costs and collection efficiencies are about the same as those for an electrical precipitator. Figure 60 illustrates

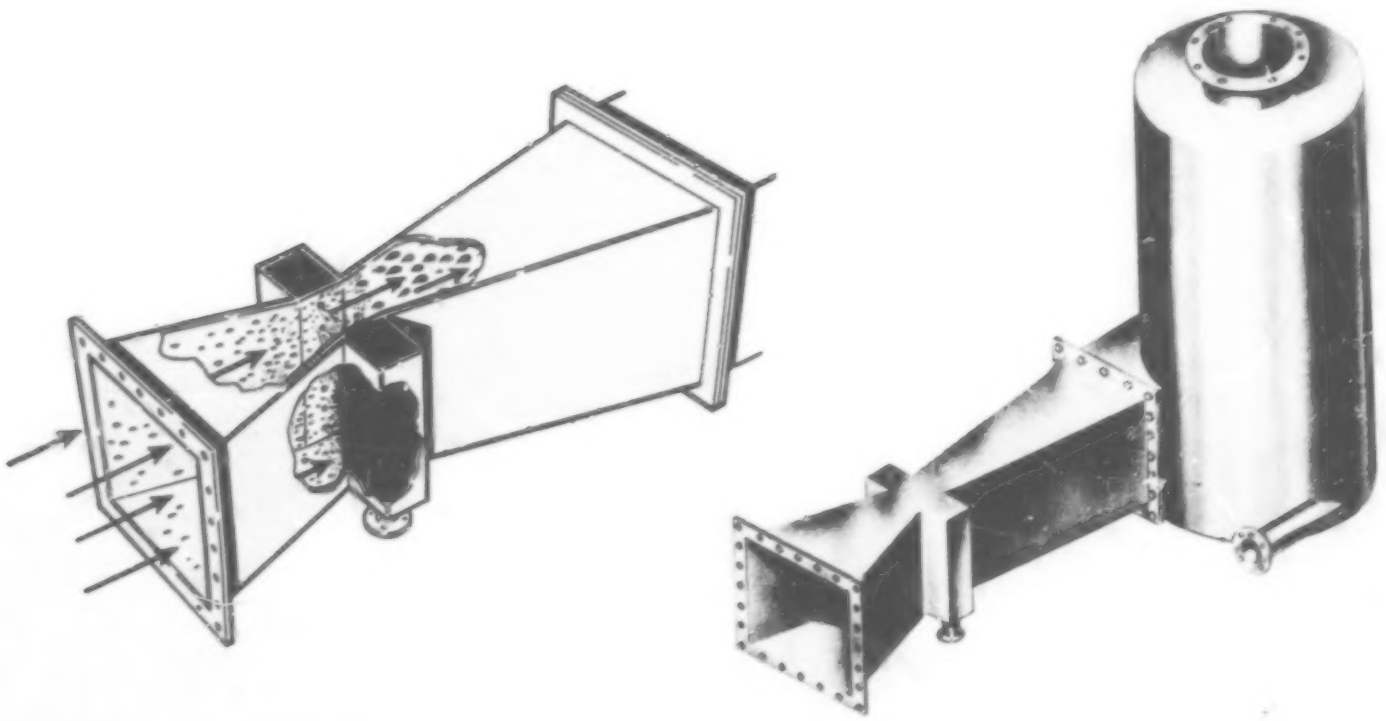


Figure 59. Venturi scrubber (Chemical Construction Co., New York, N. Y.).

one type of thin-bed tower. The packing in this device consists of lightweight glass spheres kept in motion by the air velocity.

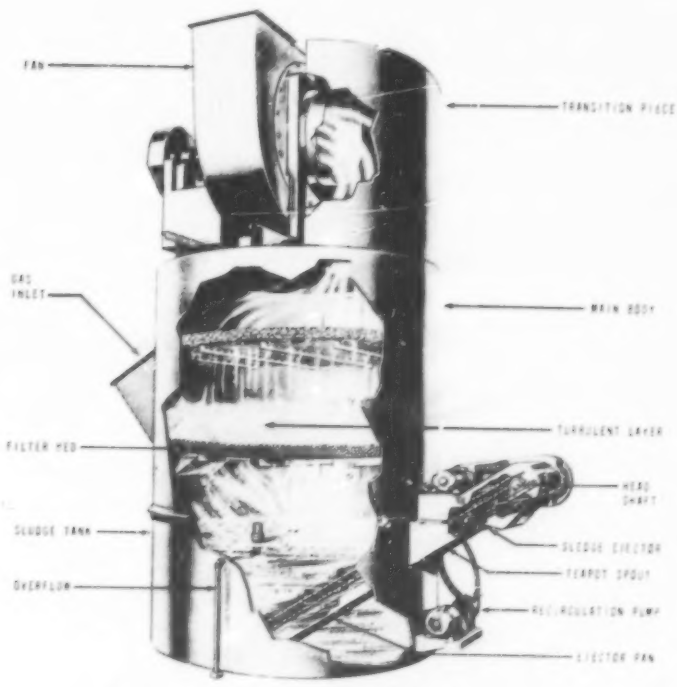


Figure 60. Thin-bed packed tower (National Dust Collector Corporation, Chicago, Ill.).

Wet Filters

A wet filter consists of a spray chamber with filter pads composed of glass fibers, knitted wire mesh, or other fibrous materials. The dust is collected on the filter pads. The sprays are directed against the pads to keep the dust washed off, as shown in Figure 61. The pads are about 20 inches square and 3 to 8 inches thick. The pads commonly used contain coarse fibers and are not very efficient for collecting fine dust. Fine glass wool fibers are efficient, but their usefulness is limited because the pads mat and sag from their supports when wetted.

Many wet collectors are a combination of the preceding types. One design consists of a spray chamber followed by impingement screens, which are followed by a centrifugal section, as in Figure 62. Several other combinations are used. The device shown in Figure 63 combines centrifugal and impingement actions. In many devices, the wetting action and collecting action take place in the same zone. Performance data on a number of different kinds of wet collectors are shown in Table 33.

THE ROLE OF WET COLLECTION DEVICES

The collection efficiency of wet collection devices is proportional to the energy input to the device. Since high-energy devices are expensive to install

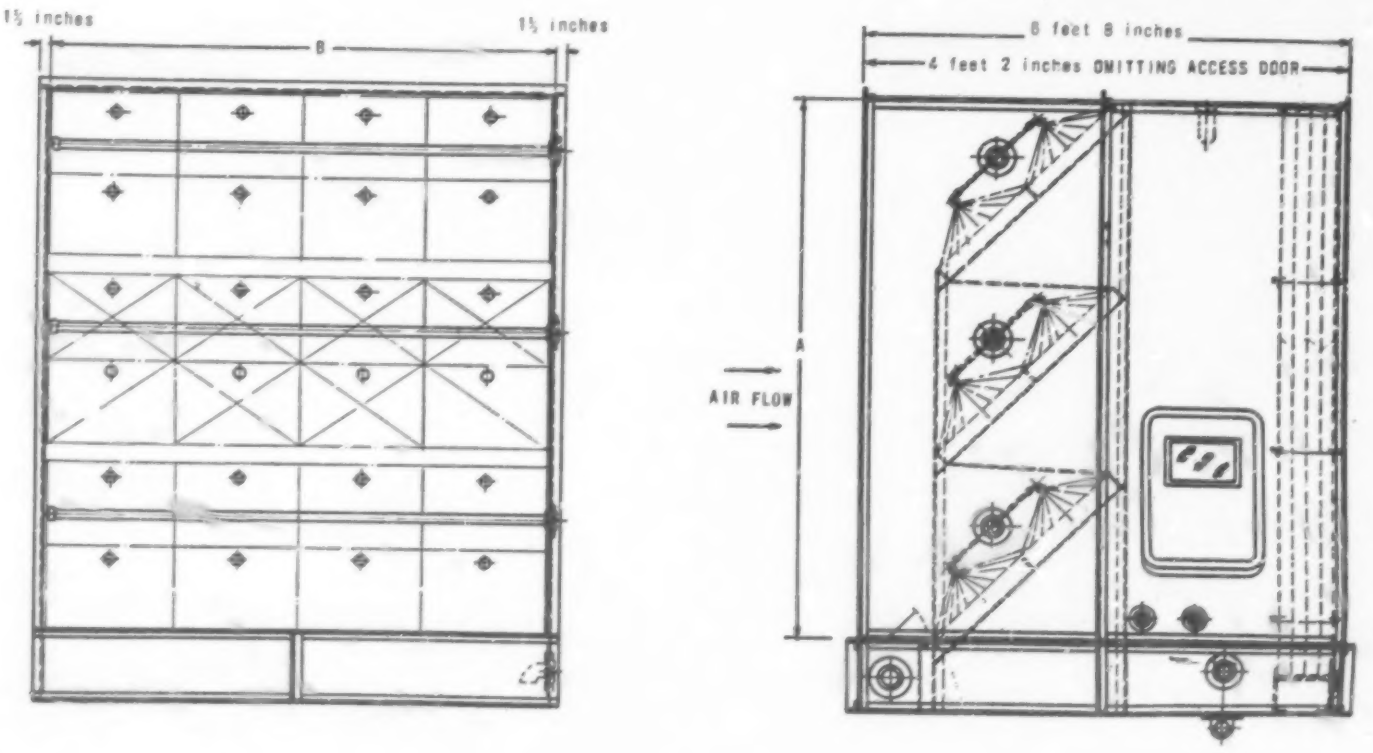


Figure 61. Wet filter (Buffalo Forge Company, Buffalo, N. Y.).

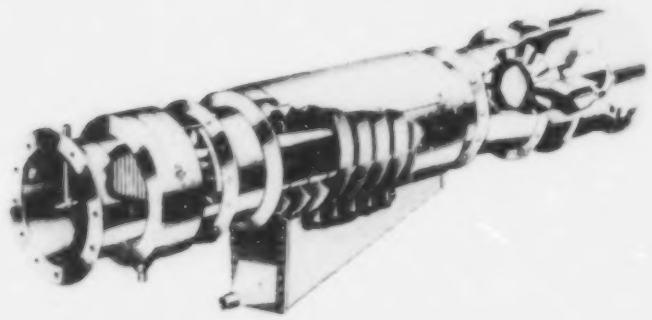


Figure 62. Multiple-action scrubber (Joy Manufacturing Company, Pittsburgh, Pa.).

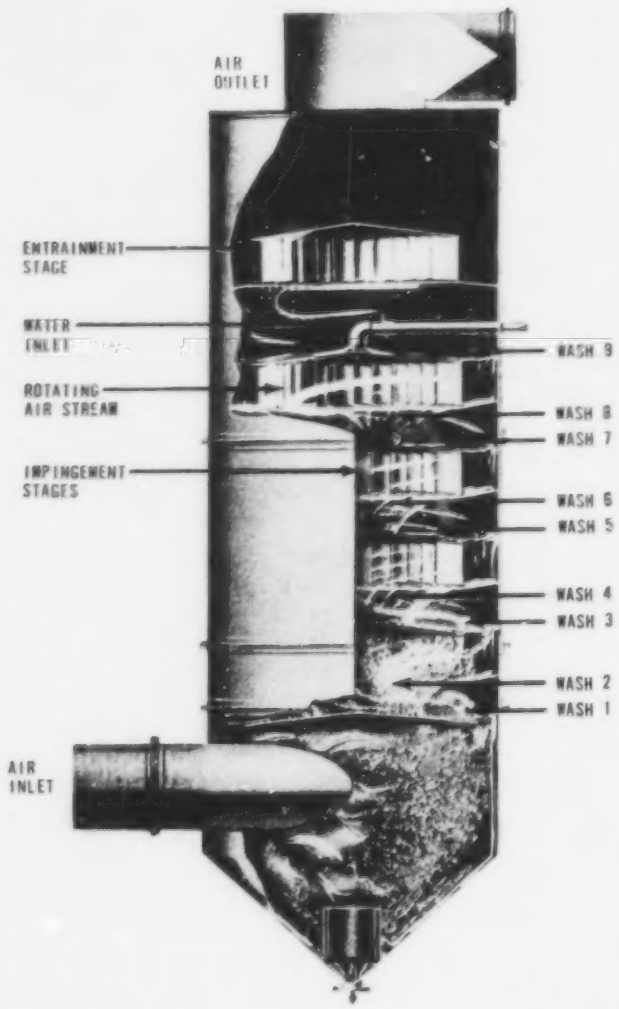


Figure 63. Centrifugal and impingement scrubber (Claude B. Schneible Company, Detroit, Michigan).

and operate, there is a natural tendency to install wet collectors of limited efficiency. In Los Angeles County, in the early days of the Air Pollution Control District, many wet collectors were found to be inadequate for meeting the emission standards. For instance, many low-energy scrubbers were installed to collect the dust from asphaltic concrete-batching plants, but they were not efficient enough to lower the emissions to the required level. A moderately high-energy scrubber was required to meet the emission limits, but even these were inadequate to reduce the emissions of grey iron cupolas to the required level. The high operating cost of high-energy scrubbers usually makes the total cost at least as much as that of a high-temperature baghouse or an electrical precipitator.

For collection of dusts and fumes, the baghouse is to be preferred over a scrubber. The positive collection mechanism of the baghouse ensures virtually complete collection of almost any dust or fume, whereas only the best scrubbers ensure good collection of very fine dusts and fumes. If, however, mists or hygroscopic particles are present in the effluent, a baghouse cannot be used. In many cases, a scrubber is the only choice. Mists that form free-running liquids when collected can be successfully collected in an electrical precipitator. If, however, sticky or gummy materials are formed, removing the collected material is very difficult, and an electrical precipitator is then impractical.

BAGHOUSES

Suspended dust and fumes may be removed from an airstream by a number of different devices. When high collection efficiency on small particle size is required, however, the most widely used method consists of separating the dust from the air by means of a fabric filter. The fabric is usually made into bags of tubular or envelope shape. The entire structure housing the bags is called a baghouse. Typical baghouses are illustrated in Figures 64, 65, 66, and 67.

FILTRATION PROCESS

Mechanisms

Filter fabrics normally used to remove dust and fumes from airstreams are usually woven with relatively large open spaces, sometimes 100 microns or larger in size (Environmental Sciences and Engineering ____; Drinker and Hatch, 1954; Spaite et al., 1961; and Stairmand, 1956). Since collection efficiencies for dust particles of 1 micron or less may exceed 90 percent (Environmental Sciences and Engineering ____), the filtering process obviously cannot be simple sieving. Small particles are initially captured and retained on the fibers of the cloth by means of interception,

Table 33. SCRUBBERS AND OTHER WET COLLECTORS
(Friedlander et al., 1952)

Device	Manufacturer	Test aerosol	Inlet concentration	Particle size at inlet, μ	Efficiency, %	Resistance H_2O	Velocity (face of wet cell), fpm	Water rate (per wet cell), gal/1,000 ft^3	Remarks
Wet cell washer (a 9-element washer consisting of 3 units in series, each made up of 3 concurrent[a] wet filter cells followed by a dry eliminator pad) (31)	Buffalo Forge Co.	Normal air	0.2 to 0.5 grain /1,000 ft^3	Most particles between 0.3 and 0.5 micron (estimated)	97	0.19 to 0.28 (per wet cell)	216	3.3 to 5	Wet cells: A. 3-in. cells of 150-μ fibers random packed 7.9 lb/ft^3
					65	0.38 to 0.56 (per wet cell)	216	3.3 to 5	B. 6-in. cells of 150-μ fibers random packed 7.9 lb/ft^3
					67	0.21 to 0.23 (per wet cell)	216	3.3 to 5	C. 8-in. cells of 255-μ fibers partially oriented, packed 4.9 lb/ft^3
		Dust composed of spheres of copper sulfate	1 to 2 grains/1,000 ft^3	2.5 (mass median)	90	Same as A	216	3.3 to 5	Same as A
					92	Same as B	216	3.3 to 5	Same as B
					94	Same as C	216	3.3 to 5	Same as C
					Cumulative efficiency stages 1 2 3				Dry pads were 2 in. thick and composed of 10-μ fibers packed 0.4 lb/ft^3 Wet cells were 8 in. thick and composed of 255-μ fibers partially oriented with densities of 3.3 lb/ft^3
Wet cell washer (an 8-element washer. Stage 1 has one counter-current[b] followed by one concurrent wet cell. Stages 2 and 3 each have one counter-current and one concurrent wet cell followed by a dry eliminator pad) (31)	Buffalo Forge Co.	Dust composed of UO_3 spheres	0.01 to 0.06 grain /1,000 ft^3	0.8 (mass median)	20 75 90	0.14 to 0.17 (concurrent) 0.22 to 0.27 (counter-current)	216	15.1	
					13 74 90	0.21 to 0.23 (concurrent) 0.32 to 0.36 (counter current) per wet cell	216	15.1	4.9 lb/ft^3 Dry pads were 2 in. thick and composed of 10-μ fibers packed 0.46 lb/ft^3
Ducon No. 8 (60)	Ducon Co.	Dust from stone and sand-drying kiln	5.8 grains/ft^3	1.5	74 (weight)			1 (rated)	Flow rate was 9,300 cfm. Temperature was 230°F in and 125°F out. Aerosol was effluent from Sirocco No. 28 cyclones.
Venturi scrubber (63)	Pease Anthony Equipment Co.	H_2SO_4 mist from sulfuric acid plant	2.92 grains/ft^3		99.7	9.7	10,260	4.1	Outlet concentration was 0.0092 grain/ft^3
			3.98 grains/ft^3		99.7	29.3	19,280	3.9	Outlet concentration was 0.011 grain/ft^3
		SiO_2 from silicon ore furnace		0.01 to 0.35	86.7	11.0	15,060	4.7	
		Iron oxide fume from open hearth furnace (oxygen lanced)	1 to 5.99 grains/ft^3	0.02 to 0.5	92 to 99 (weight)	14.0	15,840		Outlet concentration was 0.0092 to 0.069 grain/ft^3
Cyclone scrubber (62)	Pease Anthony Equipment Co.	Lime dust from lime kiln	9.2 grains/ft^3	2.0 to 40.0	99	2 to 4 (rated)		5 to 10 (rated)	Outlet concentration was 0.08 grain/ft^3
		Iron ore and coke dust from blast furnace	3.0 to 24.0 grains/ft^3	0.5 to 20.0	99 (weight)	2 to 4 (rated		5 to 10 (rated)	Outlet concentration was 0.03 to 0.08 grain/ft^3
Centri-merge (62)	Schuning Industries, Inc.	Na_2CO_3 fume	30×10^4 particles/ft^3		96.2 (count)	5.5	4,000	40	
Multi-wash (62)	Claude B. Schneible Co.	Foundry dust	99.7×10^6 particles/ft^3	< 15	88.9 (count)	4	3,380		Laboratory test

[a]Concurrent means that water is sprayed in the direction of the air flow.
[b]Countercurrent means that water is sprayed against the air flow.

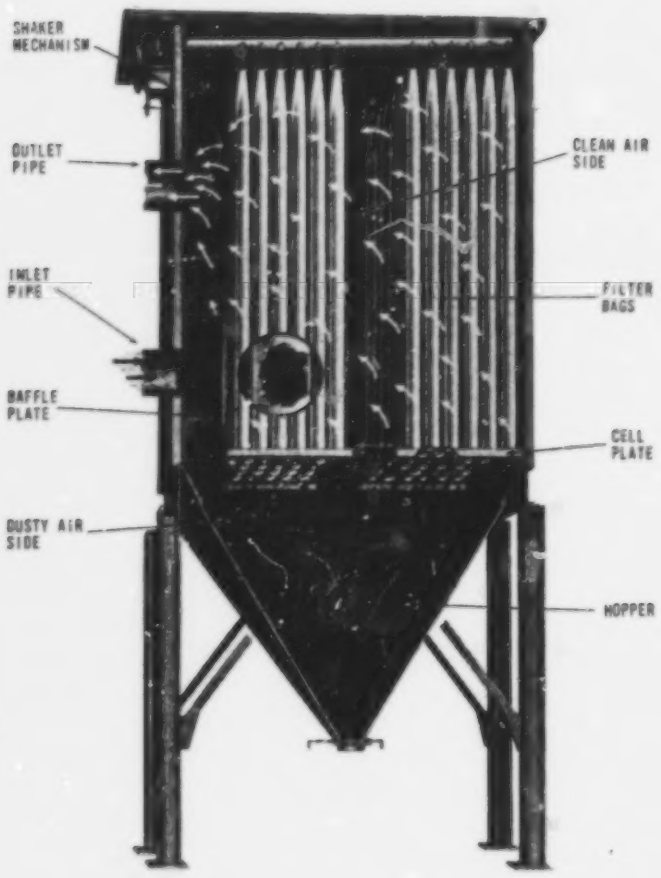


Figure 64. Typical simple baghouse with mechanical shaking (Wheelabrator Corporation, Mishawaka, Indiana).

impingement, diffusion, gravitational settling, and electrostatic attraction. Once a mat or cake of dust is accumulated, further collection is accomplished by sieving as well as by the previously mentioned mechanisms. The cloth then serves mainly as a supporting structure for the dust mat responsible for the high collection efficiency. Periodically the accumulated dust is removed for disposal. Some residual dust remains and serves as an aid to further filtering.

Direct interception

Under conditions normally existing in air filtration, the flow is almost always laminar (Drinker and Hatch, 1954; Hemeon, 1955, Rodebush, 1950; and Underwood, 1962). For conditions of laminar flow, a small inertialess particle will remain on a single streamline. If the streamline passes close to an obstruction, such as a fiber of the filter fabric, and within a distance equal to the radius of the particle, the particle will contact the obstruction and will adhere because of the van der Waals forces. While no real particle is completely inertialess, small particles of 1 micron or less may be considered, without serious error, inertialess (Rodebush, 1950).

The shape of the streamlines is not affected by the airstream velocity in laminar flow, so that collection by direct interception is independent of veloc-

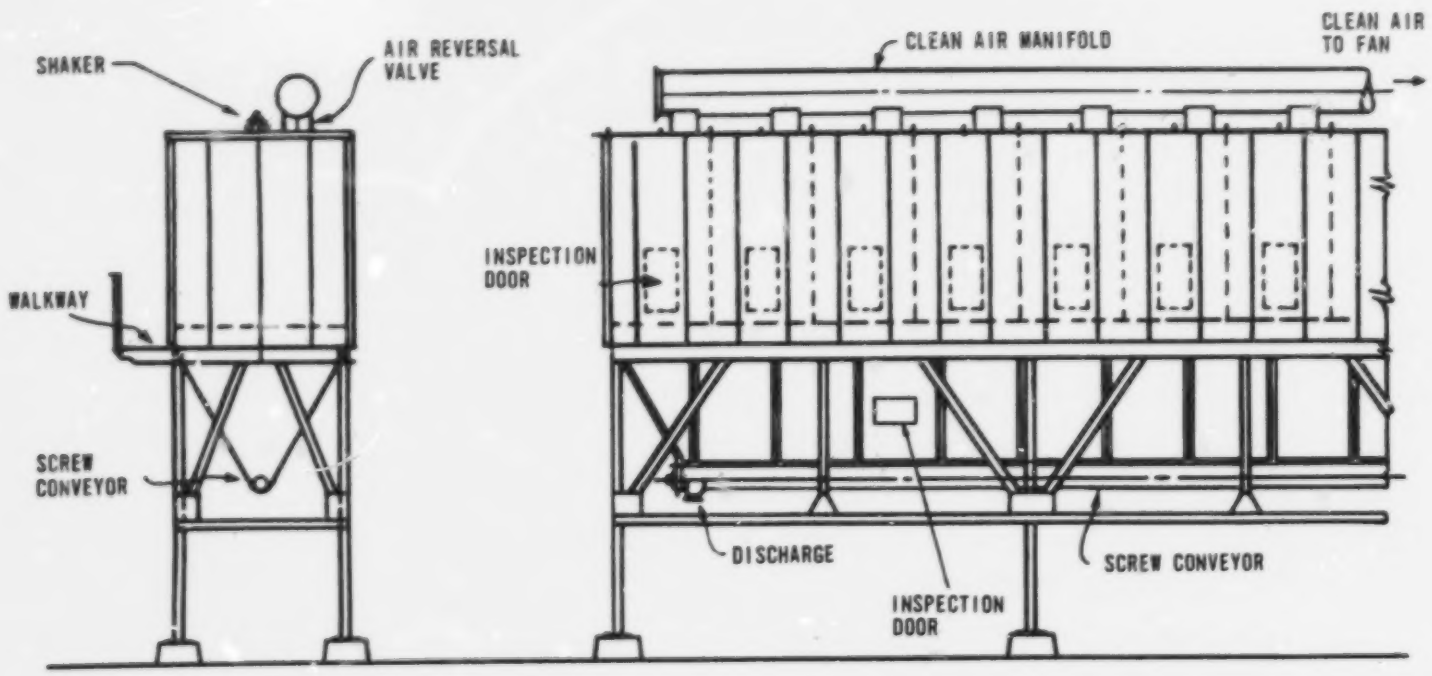


Figure 65. Fully automatic, compartmented baghouse with hopper discharge screw conveyor (Northern Blower division, Buell Engineering Company, Inc., Cleveland, Ohio).

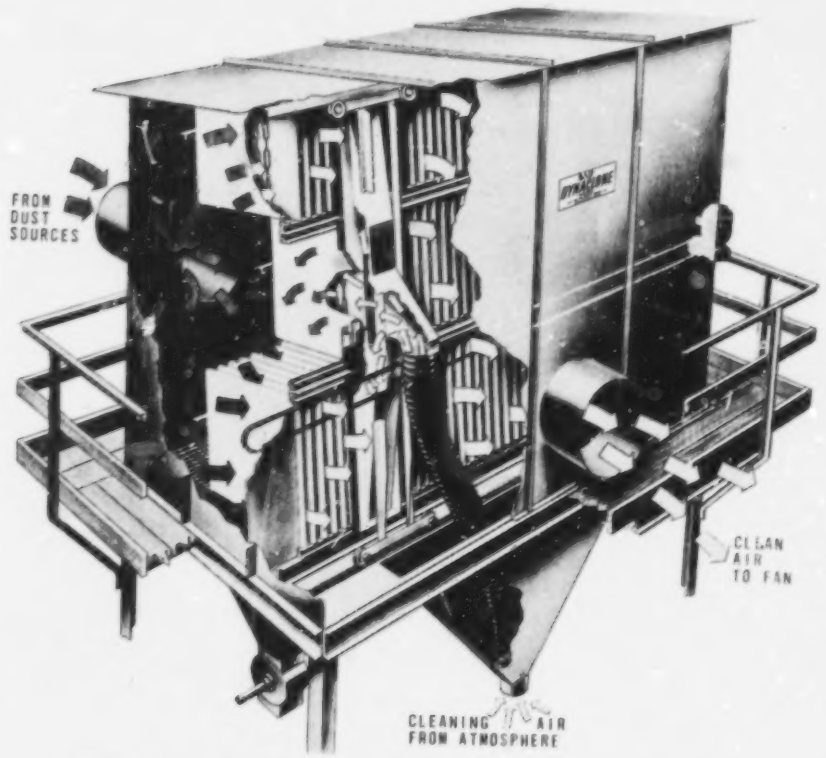


Figure 66. Envelope-type baghouse with automatic reverse-air cleaning (W. W. Sly Manufacturing Company, Cleveland, Ohio).

ity. The size of the obstruction is important since streamlines pass closer to small obstructions than they do to larger ones (Rodebush, 1950). Large particles are also collected more easily since the streamline need not pass as close, in the case of a larger particle, for the particle to contact the collecting surface. As the particle size increases, however, inertial forces rapidly increase and predominate (Ranz, 1951).

Impingement

When a particle has an appreciable inertia, it will not follow a streamline when the streamline is deflected from a straight path as it approaches an obstruction. Whether or not the particle contacts the surface of the obstruction depends upon the size of the obstruction and the size and inertia of the particle. As in the case of direct interception, smaller obstructions are more effective collectors for the mechanism of impingement or impaction and for the same reason. Other factors being equal a particle with greater inertia is more likely to strike a collecting surface.

The inertia of a particle may be measured by its so-called stopping distance. This is the distance that the particle would travel before coming to rest if the streamline were to turn abruptly at 90 degrees.

Impaction is not a significant factor in collecting particles of 1 micron diameter or less. It is generally considered significant for collecting particles of 2-microns diameter or larger (Rose et al., 1958) and becomes the predominant factor as particle size increases (Rodebush, 1950).

For effective collection of particles by inertial forces, the direction of the aerosol stream must change abruptly within a distance from the collector or obstacle approximately equal to or less than the stopping distance (Ranz, 1951). Effectively, this requires a collector with a dimension perpendicular to the aerosol stream of the same magnitude as the stopping distance (Ranz, 1951). Theoretical considerations indicate that the collection efficiency for a given size particle decreases as the collector size increases. Observations have shown that large fibers do not collect small particles well. In fact, for a given size fiber and

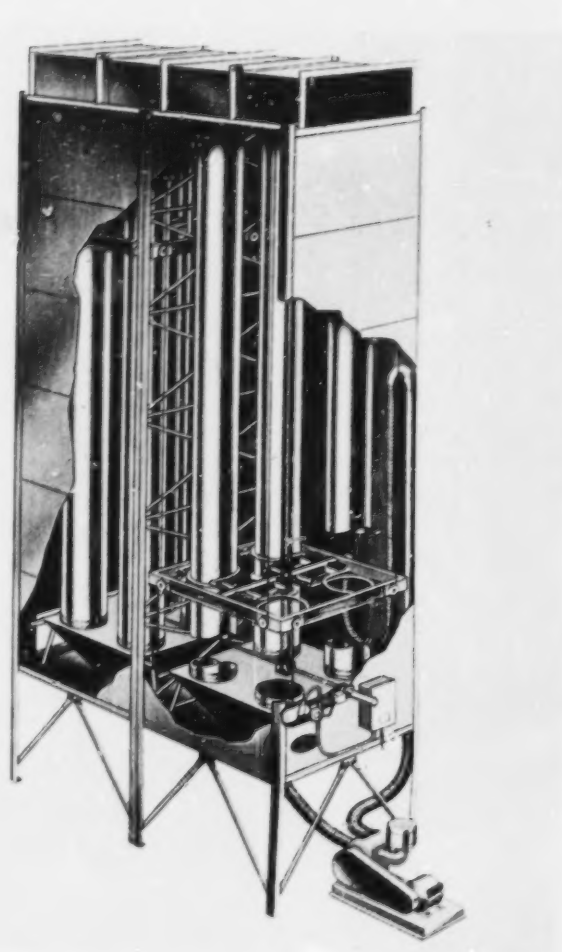


Figure 67. Reverse-jet baghouse (Western Precipitation Corporation, Los Angelas, Calif.).

airstream velocity, there is a minimum particle size below which virtually no collection by inertial forces occurs (Ranz, 1951). On the other hand, as fibers are made smaller, collection continues to improve down to the practical limits of fiber size (Rodebush, 1950).

The velocity of the airstream is important in impaction. Collection efficiency increases with increasing velocity since the stopping distance also increases with velocity. The underlying assumption is that the particle velocity is the same as that of the airstream, which is approximately true. If the velocity becomes excessive, however, the drag forces increase rapidly and may exceed the adhesive forces so that collected particles are blown off and collection efficiency decreases.

The fibers of filter fabrics are in general relatively large compared with the size of the particles to be collected. Fibers of cotton and wool, for example, are about 10 to 20 microns in diameter (Rodebush, 1950). Fibers such as these are too large to be effective collectors for particles a few microns or less in diameter. Collection efficiency for fine dusts and fumes can, therefore, be expected to be poor until a dust mat is built up on the filter fabric. This has been verified by many field observations. For a short time after new bags are installed or immediately after the bags have been thoroughly cleaned, visible emissions bleed through the fabric. In most cases, bleeding ceases in a few seconds or several minutes at the most (Rose et al., 1958). In some cases where bleeding has been a problem after each cleaning cycle, reducing the cleaning effectiveness has been found helpful.

Filter fabrics are sometimes woven from a mixture of asbestos and wool fibers to take advantage of the smaller diameter of the asbestos fibers and to improve collection efficiency on fine dusts and metallurgical fumes (Rodebush, 1950). Another method reported successful is the use of a relatively coarse dust as a precoat on the filter, which then becomes highly efficient on very fine dusts and fumes (Drinker and Hatch, 1954).

Diffusion

When particles are very small, of a dimension about equal to the intermolecular distance, or less than about 0.1 to 0.2 micron in diameter, diffusion becomes the predominant mechanism of deposition. Particles as small as these no longer follow the streamlines because collisions with gas molecules occur, resulting in a random Brownian motion that increases the chance of contact between the particles and the collecting surfaces. Once a few particles are collected, a concentration gradient is established that acts as a driving force to increase the rate of deposition (Drinker and Hatch, 1954). Lower air velocity increases efficiency by increasing the time available and hence the chance of contacting a collecting surface. Smaller collectors or obstructions also increase collection efficiency (Ranz, 1951).

Electrostatics

While electrostatics undoubtedly plays a role in the capture and retention of dust particles by a fabric filter, the evidence is inadequate to evaluate this mechanism quantitatively. According to Frederick (1961), electrostatics not only may assist filtration by providing an attractive force between the dust and fabric, but also may affect particle agglomeration, fabric cleanability, and collection efficiency. He attributes the generation of charge to frictional effects, stating that the polarity, charge intensity, and charge dissipation rate of both the dust and filter media, and their relation to each other can enhance or hinder the filtering process. He cites qualitative differences only. For example, fabric A may be better than fabric B on dust X, while fabric B is better than A on dust Y. He gives a "triboelectric" series for a number of filter fabrics that may be useful as a guide to selecting fabrics with desirable electrostatic properties. This is a fertile field for further investigations.

Until more information is available, the relative importance of electrostatics in determining the best filter fabric for a particular installation cannot be evaluated. Certainly, however, if one fabric does not work effectively, other fabrics should be tried regardless of whether the difficulty is caused by the electrostatic properties or the physical characteristics.

Baghouse Resistance

Clean cloth resistance

The resistance to airflow offered by clean filter cloth is determined by the fibers of the cloth and the manner in which they are woven together. Obviously a tight weave offers more resistance than a loose weave at the same airflow rate. Since the airflow is laminar, resistance will vary directly with airflow. One of the characteristics of filter fabrics frequently specified is the Frazier or ASTM permeability, which is defined as the air volume, in cfm, that will pass through a square foot of clean new cloth with a pressure differential of 0.50 inch WC. The usual range of values varies from about 10 to 110 cfm per square foot. The average airflow rate in use for industrial filtration is about 3 cfm per square foot, and the resistance of the clean cloth does not usually exceed about 0.10 inch WC; often it is much less.

Resistance of dust mat

Drinker and Hatch (1954), Hemeon (1955), Mumford et al. (1940), Silverman (1950), Williams et al. (1940), and others attempt to correlate the increase in resistance of the dust mat or the combination of dust mat and filter fabric with the filtration velocity or filter ratio, gas viscosity and density, dust concentration or absolute dust load, elapsed time, and dust characteristics such as particle size, true specific gravity, a particle shape or specific surface factor, and a factor for the percent of voids or the degree of packing.

The equations may approach the problem from the theoretical point of view, building up relations from basic considerations, or they may be completely practical, ignoring entirely the mechanisms involved and relating only the variables that may be measured most easily. Regardless of the approach, in the final analysis a measurement must be made experimentally to determine a proportionality constant or a "resistance factor" for the particular dust under consideration. One method (Environmental Sciences and Engineering, ____) of relating the variables follows:

$$(\Delta p)_{mat} = \frac{k \mu d (1 - \varepsilon)^2 v}{\varepsilon^3 \left(\frac{V_p}{S_p}\right)^2} \qquad (45)$$

where

$(\Delta p)_{mat}$ = pressure drop through 1 square foot of filtering area (force per unit area), lb/ft^2

k = a constant, dimensionless

μ = gas viscosity, $lb\ sec/ft^2$

d = thickness of the mat of dust particles, ft

ε = fraction of voids in the mat of particles, dimensionless

v = face velocity of the gas through the fabric, ft/sec

$\frac{V_p}{S_p}$ = ratio of particle volume to particle surface, ft^3/ft^2.

By substituting $k = \frac{K \rho_p \rho g^2 \varepsilon^3 \left(\frac{V_p}{S_p}\right)^2}{\mu (1 - \varepsilon) C}$ (46)

where

ρ_p = mass density of the particles, slugs

ρ = mass density of the gas, slugs

g = acceleration of gravity, ft/sec^2

C = dimensional constant.

and

$$d = \frac{G v t}{\rho_p g (1 - \varepsilon)} \qquad (47)$$

where

G = concentration of dust in the gas streams, lb/ft^3

t = elapsed time, sec,

it is possible to solve for $(\Delta p_t)_{mat}$, the pressure loss through the mat of dust at the end of time period t.

$$(\Delta p_t)_{mat} = K \left(\frac{G \rho g v^2 t}{C}\right) \qquad (48)$$

Values of K, the resistance coefficient, must be determined experimentally. In practice it is common to express the pressure drop in inches of water, the dust concentration in grains per cubic foot, the face velocity in feet per minute, and the time in minutes. The dimensional constant C is adjusted as required for the actual units used.

The K values are usually determined by using a scale model unit either in a laboratory or in the field, though care must be exercised in applying these results to a full-scale unit (Stephan and Walsh, 1960). If a vertical bag is used, elutriation of particles may occur, and the true value of K may vary with time and position on the bag (Environmental Sciences and Engineering ____). The measured value of K is an average value that may not be the same when the scale or configuration is changed. This is borne out by failure of some full-scale units to function as anticipated from pilot studies.

Williams et al. (1940) determined K values for a number of dusts, as shown in Table 34. These data were obtained by laboratory experiments by using an airflow of 2 cubic feet per minute through 0.2 square foot of cloth area or a filtering velocity of 10 feet per minute. The tests were terminated at 8 inches of water column, maximum pressure differential. Resistance coefficients were calculated from the relationship

$$K_1 = \frac{7,000 (h_f - h_i)}{G t v^2} \qquad (49)$$

where

K_1 = resistance coefficient, in. WC; per lb of dust; per cloth area, ft^2; per filtering velocity, fpm

h_f = final pressure drop across collected dust and filter cloth, in. WC

h_i = initial pressure drop across clean cloth, in. WC

G = dust loading, grains/ft^3

t = elapsed time, min

v = filtering velocity, fpm.

The pressure loss through the collected dust mat was found to increase uniformly with time, indicating a linear relationship between resistance and the thickness of the accumulated dust mat. The data clearly show a trend of increasing resistance with decreasing particle size. The test dust for the data on particles 90 microns or less in diameter was obtained by elutriation. In a full-scale baghouse, particularly if relatively long vertical bags are used, a substantial amount of elutriation can be expected (Stephan et al., 1960). The dust-laden gas usually enters the filter bag at the bottom and travels upward. As the gas filters through the cloth, the upward velocity decreases so that only very fine dust remains airborne to be deposited on the upper portion of the bag. Since the actual pressure loss through the bag must be the same through all areas, the volume and filtering velocity through some portions of the bag increase to excessively high values. Stephan and Walsh (1960) found that local filtering velocities vary by a factor of 4 or more over a single filter bag. This, in turn, may lead to collapse or puncture of the filter cake (Stephan et al., 1960). Punctures are small holes in the dust mat. They are usually self-repairing because the increased airflow through the small area of low resistance brings more dust with it. Collapse of the filter cake, on the other hand, is a shift in cake structure to a more compacted condition with a greater resistance. The collapse may progress in several steps.

Both collapse and puncture of the filter cake are phenomena caused by excessive filtering velocities. Some dust may be surmised to be embedded in the interstices of the cloth when puncture or collapse occur, so that normal cleaning will not completely remove it. This may lead to "blinding," which is a plugging of the fabric pores to such an extent that the resistance becomes excessively high permanently. Once it starts, blinding tends to become worse rapidly. For example, Stephan (1960) found transient local filtering velocities of about 100 fpm through areas of puncture when the average filtering velocity was only 0.75 fpm. Further evidence is cited by Lemke et al. (1960) who note that, for fumes from galvanizing operations, filtering velocities must be kept below approximately 2 feet per minute to avoid blinding and cleaning difficulties. When higher filtering velocities were employed, the residual pressure loss after cleaning increased continuously from one cleaning cycle to the next

Table 34. FILTER RESISTANCE COEFFICIENTS, K_1, FOR CERTAIN INDUSTRIAL DUSTS ON CLOTH-TYPE AIR FILTERS (Williams et al., 1940)

Dust	K_1, in. WC per lb of dust per ft^2 per minute of filtering velocity--for particle size less than						
	20 mesh[a]	140 mesh[a]	375 mesh[a]	90 μ[b]	45 μ[b]	20 μ[b]	2 μ[b]
Granite	1.58	2.20				19.80	
Foundry	0.62	1.58	3.78				
Gypsum			6.30			18.90	
Feldspar			6.30			27.30	
Stone	0.96			6.30			
Lampblack							47.20
Zinc oxide							15.70[c]
Wood				6.30			
Resin (cold)		0.62				25.20	
Oats	1.58			9.60	11		
Corn	0.62		1.58	3.78	8.80		

[a]Coarse.

[b]Less than 90 μ or 45 μ, medium; less than 20 μ or 2 μ, fine; theoretical size of silica, no correction made for materials having other densities.

[c]Flocculated material, not dispersed; size actually larger.

until the volume was adversely affected. The fume in this case was largely ammonium chloride. With lower filtering velocities the equipment functioned well.

Hemeon (1955) takes a more practical approach to the evaluation of pressure loss in cloth filtration. He notes that the resistance of clean new cloth can never again be attained once the cloth has been used. He takes, therefore, the resistance of the cloth-residual cake combination as the basic cloth resistance.

$$R_o = K_o V_f \qquad (50)$$

where

R_o = the basic cloth resistance, in. WC

K_o = resistance factor, in. WC/fpm

V_f = the filtering velocity, fpm.

The magnitude of the factor K_o depends upon the nature and quantity of dust that remains lodged in the interstices of the cloth. Thus, it depends upon the effectiveness of the cleaning action as well as upon the dust and cloth characteristics. Values of K_o are listed in Table 35. The removable dust mat contributes a varying resistance according to the relationship

$$R_d = K_d V_f W = \frac{K_d Q W}{A} \qquad (51)$$

where

R_d = the basic dust resistance, in. WC

K_d = the resistance coefficient, in. WC/fpm/oz of dust/ft^2

V_f = the filtering velocity, fpm

W = dust loading, oz/ft^2

Q = the air flow rate, cfm

A = the total cloth area, ft^2.

Values of the coefficient K_d are given in Table 36 for several different dusts and dust loadings. The total pressure drop through the filter cloth may then be calculated as the sum of the basic cloth resistance and the basic dust resistance.

$$R = K_o V_f + K_d V_f W \qquad (52)$$

Hemeon assumes that the basic dust resistance depends only upon the physical properties of the dust. Lunde and Lapple (1957) claim, however, that the resistance coefficient of the dust cake also depends upon the fabric. Too literal an application of these data and equations should not be attempted; rather they should be used as a guide to be modified according to experience and the particular situation.

Pring (1952) uses equation 49 to determine a number of resistance factors, K_2 as shown in Table 37, which also lists typical filtering velocities for several dusts.

Mumford et al. (1940) investigated the resistance of cotton filter cloth for coal dust. They performed a series of bench-scale, laboratory-type experiments using a minus-200-mesh coal dust. The results confirmed a linear relationship between the resistance and airflow rate when the dust loading was held constant. As shown in Figure 68, however, they report that the resistance varies with the 1.5 power of the dust loading when the airflow rate is held constant. Williams et al. (1940) and some other investigators report that the resistance varies linearly with dust loading.

Campbell and Fullerton (1962) also report a nonlinear relationship between resistance and filtering velocity, as shown in Figures 69 and 70. These

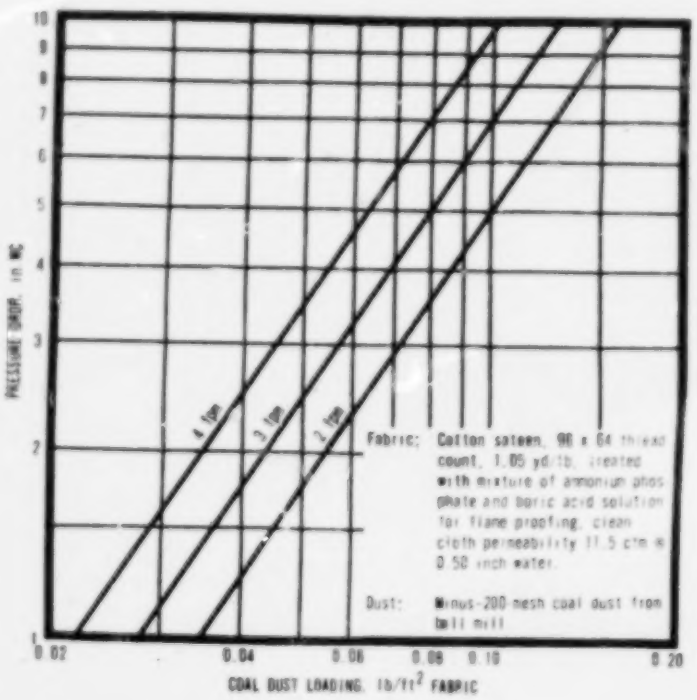


Figure 68. Pressure drop through cotton sateen cloth versus coal dust loading for different filtering velocities in a test unit (Mumford et al., 1340).

Table 35. VALUES OF THE BASIC CLOTH RESISTANCE FACTOR, K_o, OBSERVED IN SPECIFIED APPLICATIONS
(Hemeon, 1955)

Type of dust	Cloth area, ft^2	K_o
Flat bag collectors		
Stone-crushing operations	250	0.83
Stone-crushing operations	250	0.49[a]
Stone-crushing operations	500	0.83
		0.78
		0.75
		0.74
Stone-crushing operations	2,250	0.79
Stone-crushing operations	9,000	1.01
Synthetic abrasive crushing operations	--	0.80
Clay crushing in dry pan	500	1.60
Cloth tube collectors		
Stone-crushing operations	2,150	0.47
		0.45
		0.60
Stone-crushing operations	4,300	0.45
		0.37
Stone-crushing operations	1,500	0.40
Stone chiseling	400 to 1,000	0.17 to 0.27
Electric welding fume	10	0.70
Iron cupola fumes	--	2.50
Foundry dust core knockout	5,200	0.28
		0.25
		0.58
Shot blast room ventilation	2,350	0.63
		0.39
		0.39
Same--pneumatic lift	950	0.34, 0.36, 0.59
Clay crushing in dry pan	500	0.60

[a]Same as first operation but after installation of pneumatic vibrator.

data were obtained by venting a portion of the effluent from a direct-arc steel-melting furnace to a pilot model baghouse with glass fabric filtering elements. No effort was made to control or correlate the dust loading with the pressure loss.

Caplan (1954) states that pressure loss is linearly related to gas flow if, and only if, the absolute amount of dust remains constant when the gas flow rate is varied. In practice this does sometimes happen. The amount of dust generated in these cases is independent of the ventilation rate. Increasing the volume vented above that required to ensure 100 percent capture of emissions does not, therefore, increase the total amount of dust carried to the baghouse. In many cases, however, increasing the ventilation rate increases the absolute amount of particulates, though the increase in emissions may be less proportionately than the increase in gas rate. Thus, the effect on the resistance of varying the filtering velocity depends upon factors that may easily be overlooked or may be difficult to ascertain.

If the grain loading (dust concentration in the gas stream in grains/ft^3 as distinguished from absolute dust loading in lb/min) remains constant, resistance is generally considered to vary as the filtering velocity squared (Environmental Sciences and Engineering ____). The derivation of this relationship is from the linear variation of resistance with changes in volume when the absolute dust load remains constant combined with the linear variation of resistance with changes in absolute dust loading when the volume remains constant. The latter condition may be restated as a linear variation of resistance with changes in grain loading when the volume remains constant. If, however, the grain loading remains

Table 36. VALUES OF BASIC DUST RESISTANCE FACTOR (K_d) OBSERVED ON SOME INDUSTRIAL INSTALLATIONS (Hemeon, 1955)

Type of dust	Cloth dust loading (W), oz/ft^2	K_d
Stone crushing (plant A)	5	0.18
	12	0.12
	14	0.08
	17	0.12
	22	0.11
	25	0.02
	28	0.07
Stone crushing (plant B)	7	0.16
	8	0.10
	8	0.08
Stone crushing (plant C)	1	0.82
Foundry, castings clean		
Shot blasting	0.2	0.82
	0.3	0.25
	1.3	0.25
Pneumatic shot lift	0.2	0.66
	2.4	0.40
Core knockout	0.2	0.55
	0.1	0.68
Sandblasting (scale)	7	0.20

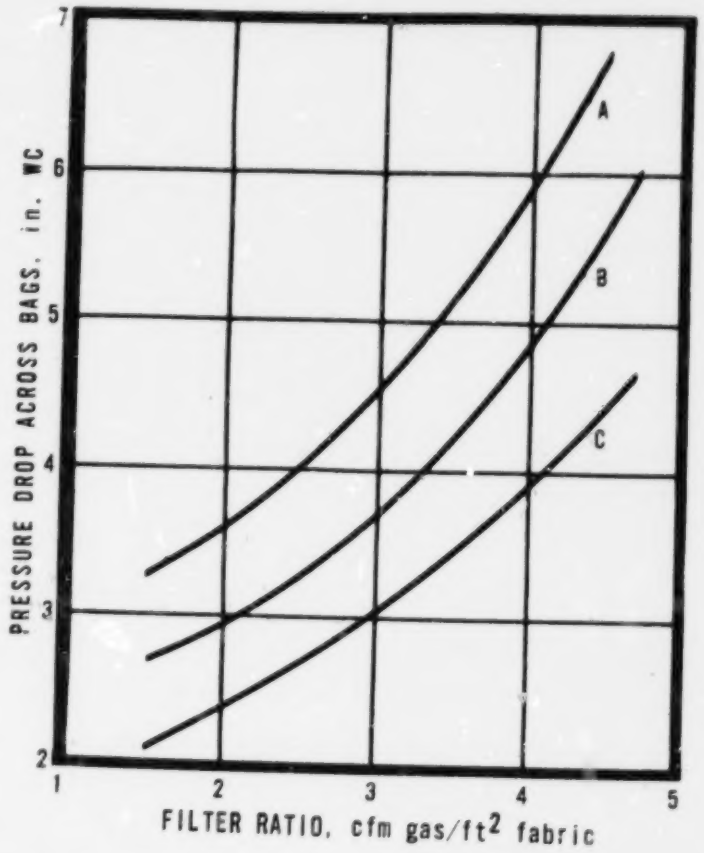


Figure 69. Pressure drop versus filter ratio for fabrics on 60-minute cleaning cycle (Campbell and Fullerton, 1962). Note that A and C are siliconized glass fabrics, B is a siliconized Dacron fabric.

Table 37. TYPICAL RESISTANCE FACTORS (K_2) AND COMMON FILTERING VELOCITIES (V) FOR SELECTED UNSIZED DUSTS (Pring, 1952)

Dust	Cloth	Resistance, factor (K_2)	Velocity (V), fpm
Nut shell dust	Cotton sateen	0.2	
Asbestos	Napped orlon	2.18	
Titanium dioxide	Cotton sateen	94 to 206	
	E-21 wool	34.6 to 70	
White lead	C-11 nylon	47 to 104	
	E-21 wool	32.2	
Copper powder	Napped vinyon	5.1 to 10.6	
Tobacco	Cotton sateen	36	
Carbon black	Napped orlon	22.4 to 28.2	1.5
Bismuth and cadmium	Cotton sateen	2.7	6 to 8
Insulating brick			4
Calcimine			2.6
Cement			1.5 to 2.7
Clay			2.9
Flour			2.7 to 3.0
Glass sand			1.2
Milk powder			4.5
Mixed pigments			2.3 to 2.9
Soap			1.6 to 3.1
Wood flour			2.8 to 4.8

constant and the volume is increased, then the absolute dust load must increase. The result is that, for a constant grain loading, resistance varies as the square of the volume or filtering velocity (Brief et al., 1956).

Silverman (1950) states that, notwithstanding the theoretical equations, an exponential relationship exists in practice and that this has been verified by Bloomfield and DallaValle.

The observation by Stephan et al., (1960) that filter resistance coefficients actually vary with time also supports an exponential relationship since the coefficients are based upon an assumed linearity.

Effect of resistance on design

In an actual installation the resistance of the cloth filter and dust cake cannot be divorced from the total exhaust system. The operating characteristics of the exhaust blower and the duct resistance will determine the way increases in baghouse resistance affect the gas rate. If the blower characteristic curve is steep, the gas flow rate may be reduced only slightly when the resistance of the filter bags changes markedly. This occurs because, as the volume decreases slightly, the pressure delivered by the blower increases proportionately more, while the duct resistance decreases, partially offsetting the increase in resistance of the filter cloth. Some variation in resistance and air volume must normally occur, however, in all baghouse installations, even in the Hersey type to be discussed later. Proper design requires the volume to

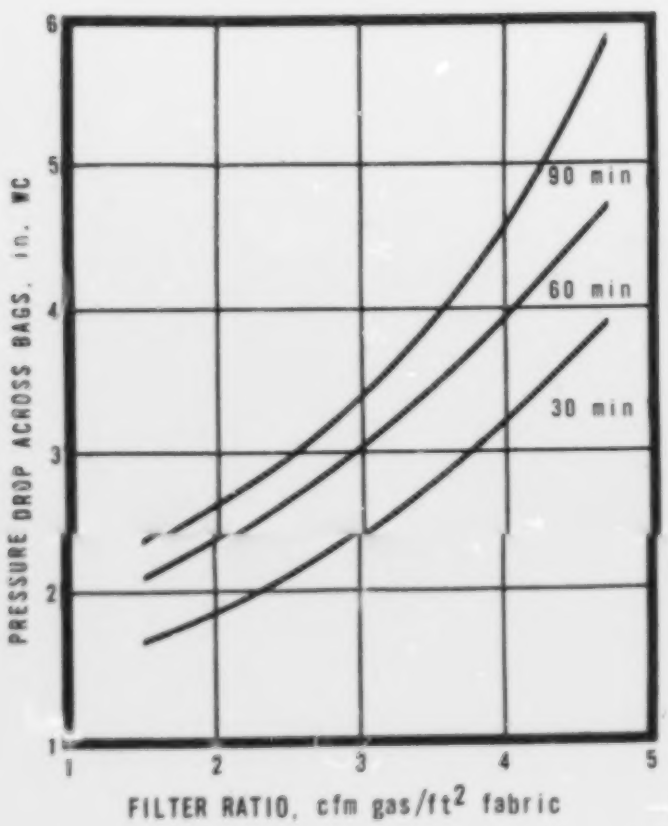


Figure 70. Pressure drop versus filter ratio for glass fabric at various cleaning cycles (Campbell and Fullerton, 1962).

be adequate to capture the emissions at the source when the system resistance is a maximum and the gas volume a minimum. At the same time, the filter ratio must not be excessive immediately after cleaning when the system resistance is a minimum and the gas volume a maximum.

Selecting or designing a baghouse requires the following initial steps:

1. The minimum volume to be vented from the basic equipment must be determined according to the principles set forth elsewhere in this manual.

2. A maximum desirable baghouse resistance must be estimated.

3. The blower operating point is selected to provide the minimum required volume at the maximum baghouse resistance.

4. A minimum baghouse resistance is estimated for the condition immediately after the filter bags are thoroughly cleaned.

5. A second operating point on the blower characteristic curve is determined for the clean bag condition.

6. The minimum filtering area required is determined by the maximum filtering velocity permissible for the particular dust or fume being collected.

7. The calculations are rechecked, with the filtering area thus determined to ensure compatibility.

The most common deficiency in selecting and designing baghouses and exhaust systems is failure to take into consideration the normal variation in air volume. The proper design approach requires that the two extreme conditions be considered separately rather than on the basis of the average, because on the average, conditions are not average.

Filtering Velocity

Filtering velocity or filter ratio is defined as the ratio of gas filtered in cubic feet per minute to the area of the filtering media in square feet. The units of filter ratio are, therefore, cfm/ft^2. By cancelling, the units of filter ratio are reduced to feet per minute, and in this form it is often referred to as filtering velocity. Physically, filter ratio, or filtering velocity, represents the average velocity with which the gas passes through the cloth without regard to the fact that much of the area is occupied by the fibers from which the cloth is woven. For this reason, the term "superficial face velocity" is often used. Filtering velocity is an important factor in filtration. Too high a filter ratio results in excessive pressure loss, reduced collection efficiency, blinding, and rapid wear. Silverman (1950) recommends values of filtering velocity from 0.5 to 5.0 fpm with an average of 3.0 for common dusts. He states, however, that the velocity should be maintained below 0.5 fpm for fumes that tend to plug fabrics. Watts and Higgins (1962) report that, for control of emissions from brass smelter operations, their experience indicates that the filter ratio must be 1.0 to 1.5 fpm or even less when spun Orlon filter bags are used. Adams (1964) recommends a maximum filter ratio of 2.0 for fumes from direct-arc steel-melting furnaces with glass bags, or 3.0 if Orlon bags are used. He estimates that average bag life under these conditions is 18 months for the glass and 5 years for the Orlon. These life figures generally appear to be too optimistic in the case of the Orlon and slightly pessimistic in the case of the glass fiber bag. Spaite et al. (1961) recommend filter ratios of 1.5 to 2.0 fpm when glass cloth is used at high temperature compared to 3.0 fpm average practice for low temperature filters. Drinker

and Hatch (1954) also cite 3.0 as a design filter ratio for typical dust and average concentrations. Stairmand (1956) gives a range of 1 to 6 feet per minute for normal fabric filters in actual practice but emphasizes the need to operate with low filtering velocities since higher velocities lead to compaction resulting in excessive pressure drop or to breakdown of the dust cake, which in turn results in reduced collection efficiency. Rose et al. (1958) observe that filter ratios range from 1 to 6 cubic feet per minute per square foot of cloth area in practice with 3.0 as a common standard for normal dusts. For metallurgical fumes, however, he recommends that the filter ratio not exceed 1/2 to 1 cubic foot per minute per square foot of cloth area. Brief et al. (1956) describe successful baghouse installations serving direct-arc electric steel-melting furnaces using Orlon bags at filter ratios of 1.91 and 1.79.

Clement (1961) emphasizes that the filter ratio cannot be too low from an operational viewpoint. This is in conflict, however, with economic considerations, which tend to prevent overdesign. His recommended maximum filter ratios for various dusts are shown in Table 38. These values represent a compromise that experience has shown optimum for minimizing total cost

Table 38. RECOMMENDED MAXIMUM FILTERING VELOCITIES AND MINIMUM DUST-CONVEYING VELOCITIES FOR VARIOUS DUSTS AND FUMES (Clement, 1961)

Dust or fume	Maximum filtering velocity, cfm/ft² cloth area	Branch pipe velocity, fpm
Alumina	2.25	4,500[c,f]
Aluminum oxide	2	4,500
Abrasives	3	4,500
Asbestos	2.75	3,500 to 4,000
Buffing wheels	3 to 3.25	3,500 to 4,000[c,or d,b]
Bauxite	2.50	4,500
Baking powder	2.25 to 2.50	4,000 to 4,500
Bronze powder	2	5,000
Brunswick clay	2.25	4,000 to 4,500
Carbon	2	4,000 to 4,500
Coke	2.25	4,000 to 4,500[a,g,h]
Charcoal	2.25	4,500[a,g,h]
Cocoa	2.25	4,000[a,e,g,h]
Chocolate	2.25	4,000[a,e,g,h]
Cork	3	3,000 to 3,500[a,b,f]
Ceramics	2.50	4,000 to 4,500
Clay	2.25	4,000 to 4,500
Chrome ore	2.50	5,000
Cotton	3.50	3,500[a,b,c,f]
Cosmetics	2	4,000
Cleanser	2.25	4,000[a,b,g]
Feeds and grain	3.25	3,500[a,h]
Feldspar	2.50	4,000 to 4,500
Fertilizer (bagging)	2.40	4,000
Fertilizer (cooler, dryer)	2	4,500
Flour	2.50	3,500[a,h]
Flint	2.50	4,500
Glass	2.50	4,000 to 4,500
Granite	2.50	4,500
Gypsum	2.50	4,000
Graphite	2	4,500

Dust or fume	Maximum filtering velocity, cfm/ft² cloth area	Branch pipe velocity, fpm
Iron ore	2	4,500 to 5,000
Iron oxide	2	4,500
Lampblack	2	4,500
Leather	3.50	3,500[c,f]
Cement crushing	1.50	4,500[c,i]
Grinding (separators, cooling, etc)	2.25	4,000
Conveying	2.50	4,000
Packers	2.75	4,000
Batch spouts	3	4,000
Limestone	2.75	4,500
Lead oxide	2.25	4,500
Lime	2	4,000
Manganese	2.25	5,000
Marble	3	4,500
Mica	2.25	4,000
Oyster shell	3	4,500
Paint pigments	2	4,000
Paper	3.50	3,500[f]
Plastics	2.50	4,500[a]
Quartz	2.75	4,500
Rock	3.25	4,500
Sanders	3.25	4,500[b,d]
Silica	2.75	4,500
Soap	2.25	3,500[a,b]
Starch	2.25	3,500[a,b]
Sugar	2.25	4,000[a]
Soapstone	2.25	4,000
Talc	2.25	4,000
Tobacco	3.50	3,500[a,b,f]
Wood	3.50	3,500[a,f]

[a]Pressure relief. [b]Flame-retardant cloth. [c]Cyclone-type precleaner. [d]Spark arrester. [e]Sprinklers. [f]Special hoppers, gates, and valves. [g]Grounded bags. [h]Special electricals. [i]Insulate casing.

when both maintenance and capital outlay are considered.

Maximum recommended filter ratios should be used as a guide only. Actual design values may need to be reduced if grain loading is high or particle size small, especially if the range of particle sizes is also narrow as in a metallurgical fume. When compartmented baghouses are used, the design filter ratio must be based upon the available filter area remaining with one or two compartments offstream for cleaning or servicing. Conventional baghouses for metallurgical fumes should in general be operated with filtering velocities in the range of 1.5 to 2.0. In some cases, however, such as lead fumes, the experience of the Los Angeles County Air Pollution Control District indicates that filter ratios must not exceed 1.0 and even less is recommended. The values listed in Table 38 may be used as a guide for other dusts.

Filtering Media

The filtering media selected for use in a baghouse must be compatible with the temperature and pH of the effluent. Maximum permissible temperatures and chemical resistance are listed in Table 39 for the various fibers normally used for filter media in dust collectors. Each type of fiber is also available in a wide range of cloth specifications, as illustrated by the data in Table 40, which lists specifications for only a few glass fabrics.

Fibers

Cotton

Cotton has been for many years the standard fiber for filter fabrics for common dusts. It is inexpensive, readily available, an effective filter media, and durable as long as the temperature is not excessive and no acid or strong alkali is present. For applications such as abrasive blasting, rock crushing, and conveying, cotton will probably continue to be the favored choice for many years.

Table 39. SUMMARY OF DATA ON THE COMMON FILTER MEDIA USED IN INDUSTRIAL BAGHOUSES

Fabric	Maximum temperature at baghouse inlet for continuous duty		Chemical resistance	
	Summary of published data, °F	Recommended maximum, °F	Acid	Alkali
Cotton	160 to 190	180	Poor	Fair
Dynel	150 to 180	175	Good	Good
Wool	180 to 235	220	Good	Poor
Nylon	200 to 290	220	Good	Poor
Orlon	200 to 350	275	Good	Fair
Dacron	250 to 350	275	Excellent	Good
Glass	500 to 700	550	Excellent	Excellent

Wool

Before the development of the variety of synthetics now available, wool was the only choice when the temperature was around 200°F or an acid condition was present. Wool or a wool asbestos mixture is still used in many metallurgical operations such as secondary lead smelters though it has been supplanted to a great extent by Dacron. In felted form, wool has been the standard fabric for use in Hersey-type reverse-jet baghouses.

Nylon

Nylon is a snythetic, organic fiber originally developed by E. I. du Pont de Nemours and Company and now produced by du Pont and other manufacturers. It is available in both staple and filament form. Nylon is relatively high in initial cost, but it has many desirable physical properties. It has excellent resistance to abrasion and flexing, toughness and elasticity, and resistance to many chemicals (Filter Fabric Facts, 1954). Its heat resistance is not, however, as good as that of Orlon and Dacron. Because of the slick surface, the filter cake may be removed with a minimum of cleaning action. Nylon, however, is rarely used in baghouses, because other synthetic fiber fabrics have higher heat resistances and, in general, are equivalent in regard to other properties.

Dynel

Acrylic fibers generally have low moisture absorption, good strength, resilience, and resistance to many chemicals and destructive organisms such as mildew and bacteria. An early acrylic-type fiber used for filter cloth was Union Carbide and Carbon Corporation's Vinyon N, a filament yarn. Vinyon N, a copolymer of an acrylonitrile and vinyl chloride, was a modification of the original Vinyon CF, which was a copolymer of vinyl chloride and vinyl acetate. A modified version of this fiber in staple form is now marketed under the name Dynel. Dynel has high chemical resistance, particularly to strong alkalies and acids, and will not support combustion (Filter Fabric Facts, 1954).

Orlon and Dacron

Du Pont's Orlon, the first of the 100 percent acrylics, is produced only in the staple form at the present time. Originally both filament and staple forms were available, but du Pont discontinued manufacture of filament Orlon about 1957. Orlon is light, strong, and resilient; it has good heat resistance and excellent chemical resistance, especially to acids (Filter Fabric Facts,

Table 40. TYPICAL SPECIFICATIONS FOR GLASS FILTER FABRICS

Fabric number	501	502	600	601	604	300	300A	313A
Average permeability	17	12	81	75	60	45 to 60	30 to 40	33
Mullen burst strength (Avg PSI)	588	593	485	595	555	400	450	540
Weight, oz per yd^2	9.36	9.50	8.27	10.00	12.50	16.30	17.67	13.50
Thread count	54 x 52	54 x 54	64 x 34	54 x 30	42 x 30	48 x 22	48 x 24	34 x 42
Weave	Crowfoot	Crowfoot	3 x 1 Twill	3 x 1 Twill	3 x 1 Twill	2 x 2 Reverse twill	2 x 2 Reverse twill	Crowfoot
Warp yarn	150's 1/2	150's 1/2	150's 1/0	150's 1/2	150's 2/2	150's 2/2	150's 2/2	150's 2/2
Fill yarn	150's 1/2	150's 1/2	Bulked 1/4	Bulked 1/4	Bulked 1/4	31/2 Staple	31/2 Staple	Bulked 1/4

From: Menardi and Co. Bulletin

1954). At the time du Pont discontinued manufacturing filament Orlon, Dacron was readily available. Since Dacron could be obtained in filament-type yarn, felt by many to be superior to staple yarn in cleanability, many users switched to Dacron at that time. Dacron, with similar physical and chemical resistance properties, was also less expensive than Orlon.

Teflon

An experimental tetrafluoroethylene fiber, Teflon, has been produced by du Pont but has received only limited use in air filtration. It has exceptional heat and chemical resistance but is also expensive (Filter Fabric Facts, 1954). A Teflon-Orlon mixture called HT1 is used when fluorides are present in the effluent in significant quantity.

Glass

Of all materials available for filtration, glass fabrics have the highest resistance to high temperatures and all chemicals (except fluorine). Its physical weakness, however, particularly its low abrasion and crushing resistance, requires special precautions and design features. Care must be taken to avoid damage by crushing in packing, shipping, and storing (Underwood, 1962). Vigorous shaking must be avoided, though gentle shaking with a period of about 50 cycles per minute and amplitude about 5 percent of the bag length is effective. The filtering velocity recommended, to avoid blinding, is usually less than for other fabrics on the same dust, since a more gentle cleaning action is required.

Yarn

The characteristics of the filter cloth depend not only on the material of which the yarn is constructed, but also upon the construction of the yarn, that is, weave, count, finish, and so forth.

Filament yarns

Filament yarns, available only in synthetic fibers, are manufactured by extruding the material through a perforated nozzle or spinneret. Individual filaments may be twisted together to form a multifilament yarn. Filament yarns have a greater tensile strength in relation to bulk and weight than staple fiber yarns do. In addition, they have a slicker surface (Filter Fabric Facts, 1954).

Staple yarns

Staple yarns of synthetic fibers are produced in a similar manner, except that the filaments are finer and shorter. One method of producing staple fibers is to strike the filaments with a blast of compressed air as they emerge from the spinneret. The staple fibers are then caught on a revolving drum from which they are gathered and spun into a staple yarn. A variation of this process is the production of a bulked filament. The bulked or textured filament is produced by using compressed air to rough up the surface of the filament as it is extruded from the spinneret (Marzocchi et al., 1962).

Cotton staple fibers are cleaned and drawn into parallel order by carding and other operations and are eventually twisted into yarns by a spinning process. Synthetic staple yarns are spun in much the same manner. The properties of spun yarn depend upon the amount of twist in spinning. A highly twisted yarn tends to resist penetration of particles into the interstices of the yarn (Filter Fabric Facts, 1954).

Classification of yarns is different between cottons and synthetics. In the cotton system, which is used for spun yarns, yarns are measured in hanks of 840 yards, and the yarn classification is the number of hanks to the pound. Cotton yarns classified as 20's are, therefore, only half the weight

of 10's. Filament yarns, on the other hand, are classified in the European denier system. This system, which originated with the old 450-meter silk skein in 5/100 gram units, has a higher denier to denote a heavier yarn. To convert, divide 5,315 by the cotton yarn number to determine the filament yarn denier (Filter Fabric Facts, 1954).

Weave

While the yarn and count are important, the weave is also an important basic element in the construction and should not be neglected. There are three basic variances of weave: Plain, twill, and satin. The differences are the result of different systems used in interlacing the lengthwise warp yarns with the crosswise filling yarns.

Plain weave

The plain weave has a simple one up and one down construction. *It permits maximum yarn interlacing* per square inch and, in a tight weave, affords high impermeability. If the count is lowered, this weave may be made as open and porous as desired. The plain weave is common in certain cotton ducks and many synthetic constructions (Filter Fabric Facts, 1954).

Twill weave

The twill weave may be recognized by the sharp diagonal twill line formed by the passage of a warp yarn over two or more filling yarns, the interlacing moving one pick forward with each warp. In equivalent constructions, twills have fewer interlacings than the plain weave and, hence, greater porosity, though this naturally depends on the count. Cotton and synthetic filter twills are widely used (Filter Fabric Facts, 1954).

Satin weave

The satin weave, with even fewer interlacings spaced widely but regularly, provides smooth surface and increased porosity. These qualities make them particularly valuable in gaseous filtration such as dust collection. Cotton fabrics in this weave are commonly known as sateens. Cotton sateen is probably more widely used than any other fabric in baghouses for use at ambient temperature (Filter Fabric Facts, 1954).

Finish

Dimensional stability is an important factor in filter fabrics. Cotton and wool fabrics must be preshrunk. Synthetics are generally given a corresponding treatment called heat-setting. This process contributes to a more even balance of warp and filling yarn tension, provides better surface smoothness, reduces yarn slippage, controls porosity, and virtually eliminates shrinkage, provided the fabric is not subsequently exposed to excessive temperature. The dimensional stability may be lost if the fabric is subjected to temperatures approaching that used in the original heat-setting process. It is not unusual to observe bags that have been subjected to excessive temperature with shrinkage of 3 or 4 percent. This amounts to approximately 3 to 5 inches for a 6-inch-diameter bag of average length. As a result of the shrinkage, the bag may pull loose from its connection to the floor plate or the upper support structure. In some cases extensive damage to the baghouse structure has occurred as a result of shrinkage.

Glass fabric bags are also given a treatment with silicones derived from phenylmethyl silanes or dimethyl silanes (Marzocchi et al., 1962). Glass filter fabrics may be constructed of filament, staple or bulked (texturized) yarns, or a combination of these. An organic size or binder is applied to the glass fiber as it is extruded. This later protects the fibers during the manufacturing processes necessary to produce a fabric. After weaving, the fabric is given a heat treatment. During this treatment the organic size or binder is burned off, and subsequently the silicone is applied, which serves as a lubricant to protect the individual fibers from abrasion on each other.

Glass fabric is woven from multifilament yarns. In one case investigated in Los Angeles County, fumes from a gray iron cupola were found deposited among the fibers of the yarn. This effectively prevented relative motion of the individual fibers when the cloth was flexed. The result was an apparent weakening of the cloth and a greatly reduced bag life. This is thought to be a result of the increased stress in the outer fibers of each multifilament element because the yarn was forced to bend as though it were a single solid fiber instead of a bundle of individual fibers. Other factors being equal, the maximum stress introduced by flexure is proportional to the radius of the fiber. Washing the fabric with water and detergent removed the fume and restored the cloth to its original strength. This illustrates the importance of using the silicone coating as a lubricant to permit the individual fibers to slide upon one another as the cloth is flexed. Failure of the silicone coating to function as intended results in rapid deterioration of the fabric. Laundering glass filter bags periodically has become routine in a number of plants in Los Angeles County. A common practice is to maintain two complete sets of bags. One set is laundered while the second is in use. The bags usually last through several launderings.

Heat treatment relieves the stresses introduced into the fibers because of the processes to which they are subjected during fabrication of the yarn and cloth. A permanent set is also put into the glass fibers as a result of the heat treatment

(Marzocchi et al., 1962). During the heat treating process, glass fabrics may be subjected to temperatures of from 700 to 1,200°F. It is not, however, recommended that these fabrics be exposed to such high temperatures during use. The most important reason for this is that the silicone coating undergoes a gradual deterioration at temperatures approximately greater than 500°F (Spaite et al., 1961). The rate of deterioration of the silicones increases with increasing temperatures. Thus, short periods of operation at temperatures of 600 to 700°F are permissible, but continuous operation at these temperatures will materially shorten the life of the fabric. Tests have shown that increased life can be attained by an additional treatment with graphite (Spaite et al., 1963). At present, the additional cost of the graphite treatment does not appear to be warranted for most high-temperature operations, but additional developments in this area may produce a superior filter fabric for high-temperature operation.

Size and Shape of Filters

Diameters of tubular filtering elements

The most common shape of filter elements used is a simple, circular cross-section tube. Most standard commercial units employ tube diameters of 5 or 6 inches. Filter cloth is provided in several standard widths. One common size is approximately 38 or 39 inches wide. Two 5- or 6-inch-diameter bags can be obtained from a single width of cloth, the necessary seam being allowed. For high-temperature applications, an 11-1/2- or 12-inch-diameter glass fiber bag is most commonly employed. Again, this is the most economical size for the 38-inch-wide glass cloth that is readily available. A few baghouses are designed for use with 7- or 8-inch-diameter bags. This size is probably based upon a 54-inch-wide cloth from which two bags can be obtained from a single width. Wool felts, which are used in the Hersey reverse-air jet baghouses, are generally either 9 or 10 or 20 inches in diameter. In general, bag diameters are determined mainly by the available widths of yard goods.

The diameter of the filter bags used also influences the size of the baghouse. For example, about 1,750 square feet of filtering area can be provided in about 80 square feet of floor area by using 6-inch-diameter by 10-foot-long bags. If 12-inch-diameter bags were used instead, they would need to be about 14 feet long to provide the same filtering area in the same floor space, though 12-inch-diameter bags can easily be made 20 feet long if there is adequate head room. This results in a baghouse having about 2,500 square feet of filtering area in the same floor space.

Length of tubular bags

The length of cloth filter elements varies from about 5 feet to approximately 30 feet. Most standard baghouses employing 5- or 6-inch-diameter bags use bag lengths from 5-1/2 feet to 10-1/2 feet. The lengths for 11-1/2- or 12-inch-diameter bags are generally about 15 to 25 feet.

Length-to-diameter ratio

Manufacturers have apparently not attempted to establish a standard length-to-diameter ratio. Indeed, from a theoretical point of view, the length-to-diameter ratio should have no effect on the collection efficiency of a bag except for the influence of elutriation as previously discussed. This ratio is, however, important from another aspect. Assume an extreme case of a 30-foot-long and 5-inch-diameter bag. When shaken, such a bag will sway excessively. This could easily result in one bag's rubbing upon the adjacent bag, which would be detrimental to good bag life. Another aspect of the problem concerns the cleaning of the bag by means of shaking. In order to clean the bags adequately, sufficient force must be applied to break up the dust cake and dislodge some of the embedded dust from the fabric. Studies have shown that, as the force applied is increased (as measured by the acceleration given the bag by the shaking mechanism), there is an increase in the effectiveness of the cleaning up to a limiting value (Walsh and Spaite, 1962). The studies have also shown that the residual dust profile varies along the length of the filter tube. This is a result both of the manner in which the shaking force is transmitted to the tube, and of the variation in dust cake properties. The efficiency of cleaning by means of mechanical shaking varies depending upon the length-to-diameter ratio, though the manner of variation is not known. Obviously, there is an optimum length-to-diameter ratio that may differ for different cloths, dusts, shaking intensities,and shaking frequencies (Stephan et al., 1960). Another factor that effectively limits the length-to-diameter ratio is the difficulty of fabrication. Sewing the longitudinal seam becomes increasingly difficult as the length of the bag increases. Continuous tube weaving could, however, be employed, if increased lengths were advantageous.

Substantially more investigation is needed in this field. At present, additional filtering area is apparently frequently incorporated by increasing the length of the filter tubes. When the length appears to be unreasonably long or if there is a limitation on head room, then the number of filter tubes is increased.

An absolute limiting length of 30 times the diameter has been suggested by Silverman (1950),

based upon some unspecified experiments in metallurgical baghouses. Some installations using 11-1/2- or 12-inch-diameter bags operate successfully with bag lengths up to about 30 feet. These are, however, exceptional instances, and a more practical limit appears to be about a 20-to-1 length-to-diameter ratio. Most 11-1/2-inch-diameter bags in Los Angeles County are made of glass cloth and are 15 to 20 feet long (Crabaugh et al., 1954). Greater length increases the stress because of the greater weight that must be supported by the fabric. If mechanical shaking is used, cleaning may be less effective unless more energy is applied to each bag. This also increases the stress. In high-temperature installations, dimensional instability may be increased. Problems of stretching and shrinking may occur at times, which could be mitigated by using shorter bags so that the same percent change in length would not be excessive in absolute amount. Capital outlay and floor space are both reduced with an increase in bag length while maintenance is increased. Many 5- or 6-inch-diameter bags are 8 to 10 feet long. Although no data establish an optimum length-to-diameter ratio, a 20-to-1 ratio appears to be an approximate practical limit. This is one of many areas in baghouse design that could benefit from further study.

Multiple-tube bags

A variation of the tube-type bag is oval in cross-section with vertical stitching that divides the bag into several compartments. When inflated, each compartment assumes a nearly circular cross-section.

When the blower is turned off and the pressure relieved, the bag returns to an oval shape, which helps to break up the filter cake. A bag such as this requires a special mounting and is somewhat more expensive for the same filtering area than a standard round tubular bag. It has an advantage in that a greater filtering area can be accommodated in the same size housing. There is, however, a disadvantage in that a hole in one of the bags effectively destroys a greater filtering area, and maintenance cost could thus be substantially higher than for a conventional baghouse in some cases.

Envelope type

Baghouses with envelope-shaped bags are second only to the tubular-type bag in a number of units in use. The filtering elements must be mounted on a supporting structure usually made of wire. In comparison to other designs, the envelope-type baghouse permits a greater filtering area to be installed in a given size volume. Inspection and maintenance are, however, not as easily accomplished as for the simple tube-type bag. Wear is increased because of the friction between the filter cloth and the wire frame support structure. It would not be advisable, therefore, to use this type of bag for application where rapid wear of the filter media is anticipated. Applications for temperatures in excess of 300°F are, therefore, ruled out completely because glass cloth is not able to withstand the abrasion. Only a relatively few baghouses of this type are used with synthetic filter fabrics such as Orlon or Dacron for intermediate temperatures. Dust is collected on the outside of envelope bags as opposed to the inside of tubular-type bags.

INSTALLATION OF FILTERS

Arrangement

The arrangement of tubular bags shown in Figure 71 can materially affect the number of bags that can be installed in a given area. The staggered arrangement is not as desirable as the straight, even though it uses the area more efficiently, because access for maintenance, inspection, and bag replacement is more difficult.

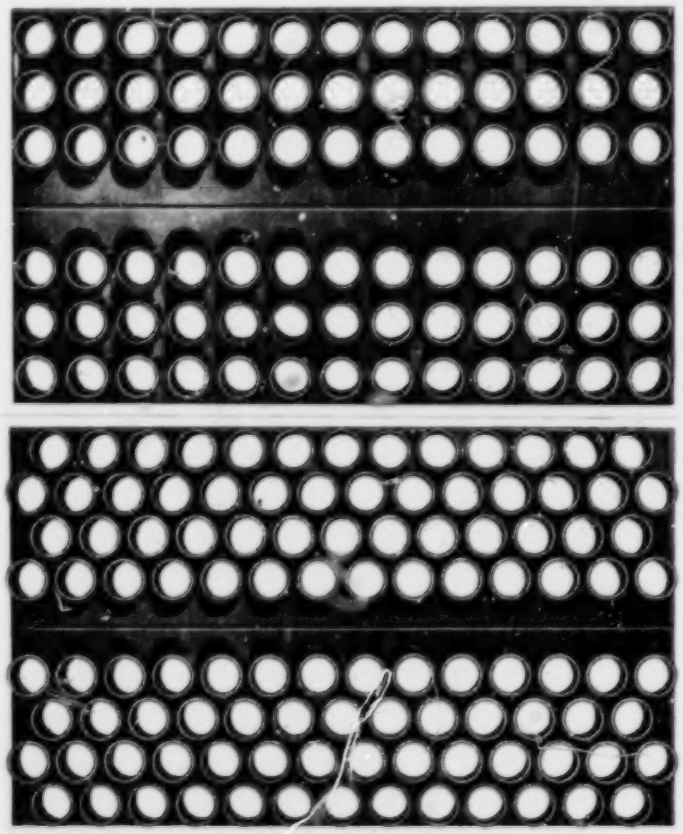


Figure 71. Arrangements of filter bags: 78 bags arranged in line (good); 108 bags in staggered arrangement in same size housing (poor) (Northern Blower Division, Buell Engineering Co., Inc., Cleveland, Ohio).

Bag Spacing

The clearance between bags is important for at least two reasons. First, sufficient clearance must be provided so that one bag does not rub upon its neighbor. This is particularly important for baghouses employing mechanical shaking where the vibration may cause the bags to oscillate. A minimum clearance of 2 inches is suggested between bags of average length. Larger clearances should be provided if the bags are unusually long, for example, greater than 10 or 12 feet. Second, access for examination and maintenance must be provided.

Walkways between banks of bags must also be provided. The depth of banks should not be so great that it is difficult or impossible to reach to the farthest bag for maintenance and replacement. This means that if a walkway is provided on one side only, each bank should be no more than three or four bags deep if 6-inch-diameter bags are used. Twelve-inch-diameter bags should not be more than two bags deep if access is provided on one side only. If access is provided on both sides, 6-inch-diameter bags must not be more than eight bags deep, and 12-inch-diameter bags must not be more than four bags deep. The total number of bags in a bank depends upon the shaking mechanism employed. A single bank, in general, is operated by a single shaking mechanism. A single compartment may contain several banks of bags.

Walkways must be provided so that all portions of the mechanism are easily accessible. Walkways should be at least 18 inches wide; a 24-inch width is recommended. When the bags are longer than about 10 or 12 feet, a walkway should be provided at two levels, one at the floor plate and a second for access to the upper support structure.

Bag Attachment

Bottom attachments

Tubular bags are most frequently attached to a thimble on the tube sheet or floor plate, as illustrated in Figure 72. A steel band is installed around the bag bottom to effect a tight seal between the cloth and the thimble. A cuff may be sewn into the bottom of the bag, or the bottom may be folded up once or twice to form a self-cuff. This is the simplest, most trouble-free arrangement and probably the most widely used means of attaching tubular bags at the bottom. The steel bands should be made of stainless steel to avoid rust and corrosion problems. A simple screw-type closure mechanism is usually employed, but quick-closing clamps, as shown in Figure 72, are also available.

In a second method of attachment, a spring steel band sewed into the bottom cuff of the bag is used. The steel band is collapsed, inserted into a hole in the floor plates, and allowed to expand. A tight seal is required between the bag cuff and the hole to prevent leakage; this requires a perfect fit. A strip of padding is sewed into the cuff to help adjust for size variations of the steel band and of the hole. Because variations in size are inherent in all manufacturing processes, it is difficult to achieve sufficient uniformity of the bag and hole to ensure a dustproof fit between them. This has been tested by the Los Angeles County Air Pollution Control District on baghouses that serve direct-arc steel-melting furnaces. Dust and fume losses are usually 5 to 10 percent that in the effluent stream entering the baghouse and not infrequently are greater. For comparison, dust and fume losses from baghouses serving similar furnaces, but with bags attached by other methods, are usually 1 to 2 percent that in the effluent stream entering the baghouse. Fitting a spring steel band into a recessed hole in the cuff of the bag permits more rapid installation. When relatively coarse dusts are involved, adequate collection efficiency can be attained, provided extra care is taken when new bags are installed to make sure that the bags fit well and are seated properly in the retaining hole.

Top support

The top of the bag may also be installed over a thimble by using a steel band in a manner similar to that used with a thimble at the bottom. When a thimble is used, the bag may have a cuff sewed into it, or the end of the bag may be folded to form a self-cuff. In most cases when mechanical shaking is employed, this type of attachment offers an advantage, since wear is usually most severe near the bottom of the bag. The life of the bag can usually be extended substantially by making the bags extra long, folding the extra material under the clamp at the top, and then lowering the bag periodically about 3 to 4 inches at a time. Bag life may be further extended by reversing the bags, top to bottom, provided this is done before wear proceeds too far.

Another method consists of attaching the bag onto a steel disc or cap, which is supported at the center, as illustrated in Figure 73. A common method of attaching 5- or 6-inch-diameter bags consists of sewing a loop at the end of the bag; the loop is then placed over a hook as shown in Figure 73. Another method involves sewing the end of the bag into a flat strap, which

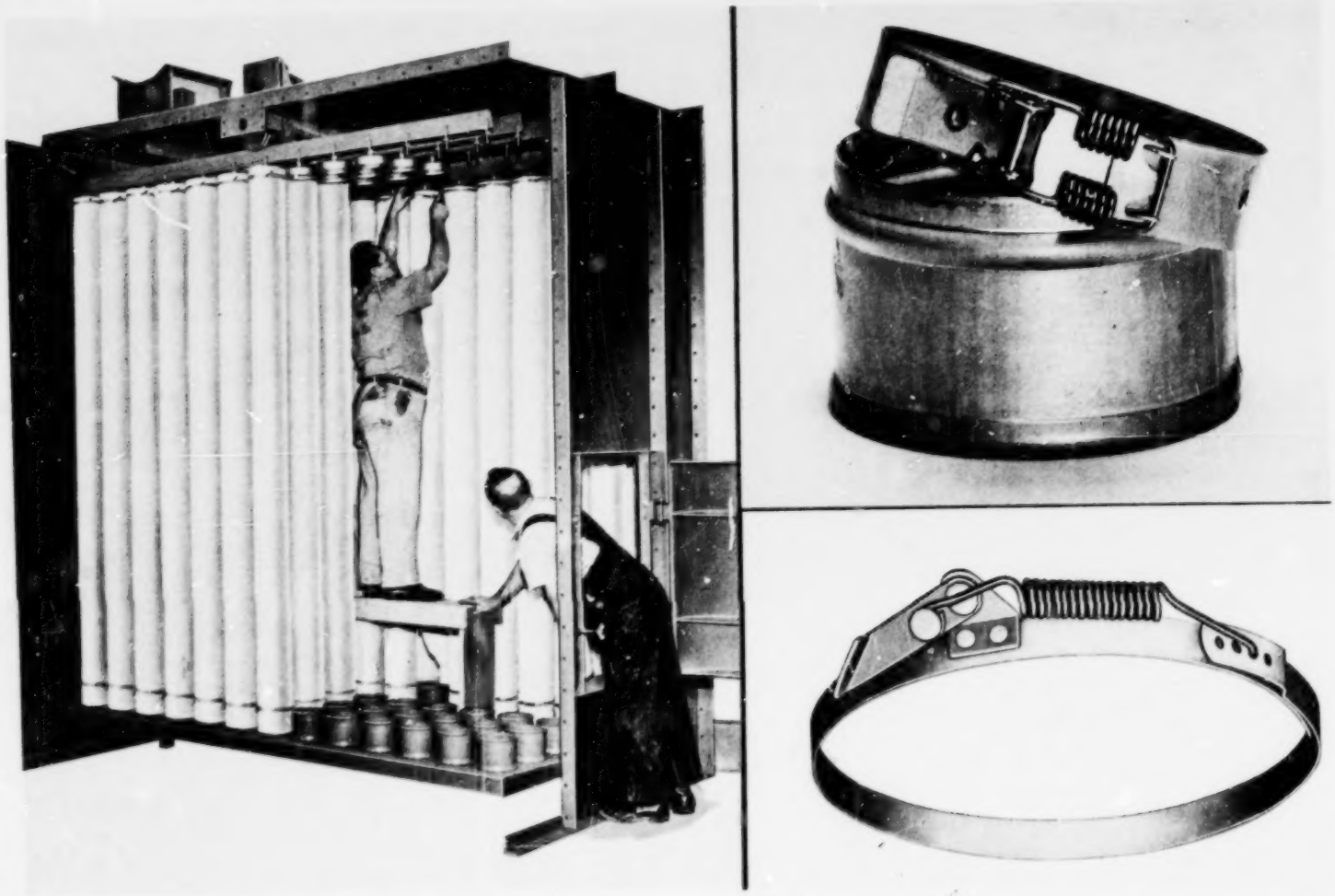


Figure 72. Connection of filter bags to thimbles: Men attaching filter bags and two examples of quick closing clamps (left and lower right, Northern Blower Division, Buell Engineering Co., Inc., Cleveland, Ohio; upper right, Fuller Company, Dracco Division, Cleveland, Ohio).

is looped back and forth over a special hanger as illustrated in Figure 74. This method is simple and permits rapid installation. The length of the bag is not critical, since adjustments are easily made during installation or at any time thereafter.

Some bags of this type, which have a strap at the upper end, were found to be developing small holes near the top of the bag. The same situation was found to be developing in several baghouses using bags of the same design and manufacture. Investigation revealed that the construction used resulted in a stress concentration in a small area of the bag. This problem was eliminated by using a different sewing technique.

CLEANING OF FILTERS

Methods

As dust accumulates on the filtering elements, the pressure loss increases until some maximum desirable value is reached. The filter must then be cleaned to reduce the pressure loss. Cleaning cycles may be manual, semiautomatic, or fully automatic. Fully automatic cycles may be initiated on a time cycle or when the pressure reaches a preset amount. Figure 75 shows a pressure switch with this function. Some reverse-jet baghouses operate with continuous cleaning. Once a cleaning cycle is initiated, it should be carried through to completion with sufficient cleaning intensity and time duration to ensure thorough cleaning. Thorough cleaning is also recommended each and every time the blower is turned off (Stephan et al., 1960).

Manual cleaning

Small baghouses with up to about 500 or 600 square feet of filtering area are frequently cleaned by hand levers. A manually operated handle transmits a rap to the framework from which the filtering elements are suspended. This shakes the dust loose. Thorough cleaning is rarely achieved since a great amount of

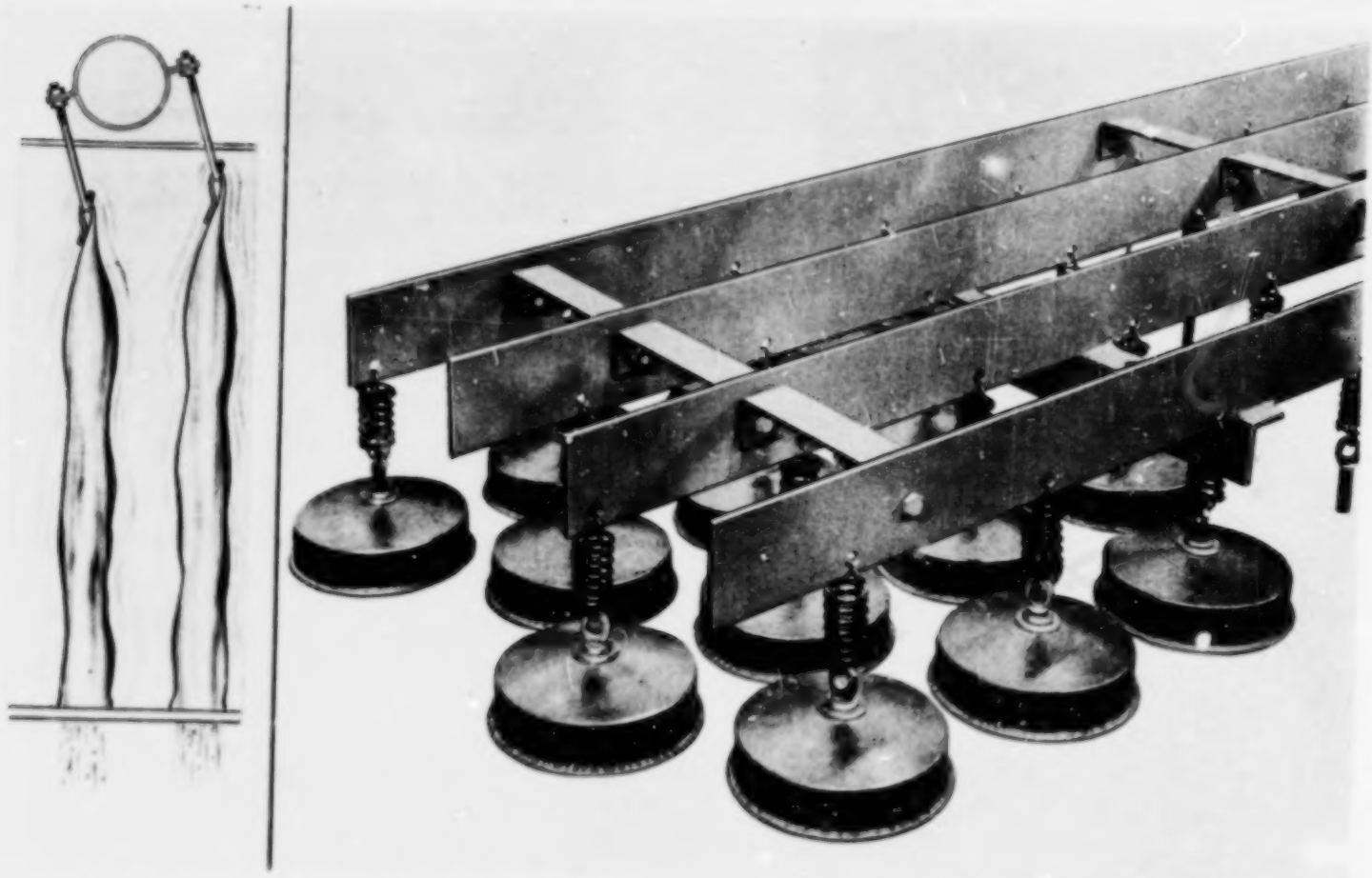


Figure 73. Connection of filter bags to top support: (a) bag loop and hook (Wheelabrator Corporation, Mishawaka, Indiana), (b) caps for use with clamps (Northern Blower Division, Buell Engineering Company, Inc., Cleveland, Ohio).

vigor must be applied continuously for several minutes. Many workmen are not aware of the amount of cleaning required or are not conscientious enough to clean the baghouse thoroughly each time. Since these small baghouses rarely have manometers to indicate the pressure, the operator cannot readily determine when the baghouse has been adequately cleaned. The use of a manometer appears to be almost essential. One must, of course, shut the fan off or otherwise deflate the bags before starting to clean them.

Mechanical shakers

Most baghouses employ some type of mechanical shaking. The electric motor shaker is most common. A cam or eccentric translates the rotary motion of the motor into an oscillation. Bags may be shaken horizontally or vertically.

It is essential that there be no pressure inside a tubular filter bag during the shaking cycle. A pressure too small to be measured with a manometer may still be sufficient to interfere with adequate cleaning (Herrick, 1963). In one investigation a pressure as small as 0.02 inch of water column prevented effective cleaning (Mumford et al., 1940). Butterfly-type dampers, unless they are positive seating, cannot be used to close off a section for shaking while the blower is operating. For this reason, a small amount of reverse airflow is commonly used to ensure complete bag collapse during shaking unless the blower is off during the cleaning cycle. When the baghouse serves a hot source such as a furnace, the thermal drive may be sufficient to interfere with cleaning even after the blower is off.

Pneumatic shakers

Two types of pneumatic cleaning mechanisms are used. In one type the air is used to operate an air motor that imparts a high-frequency vibration to the bag suspension framework. Although the frequency is high, the amplitude is low. This method is not effective for materials difficult to shake loose from the bags, since the total amount of energy imparted to the bag is low. For dust from sandblasting operations, the meth-

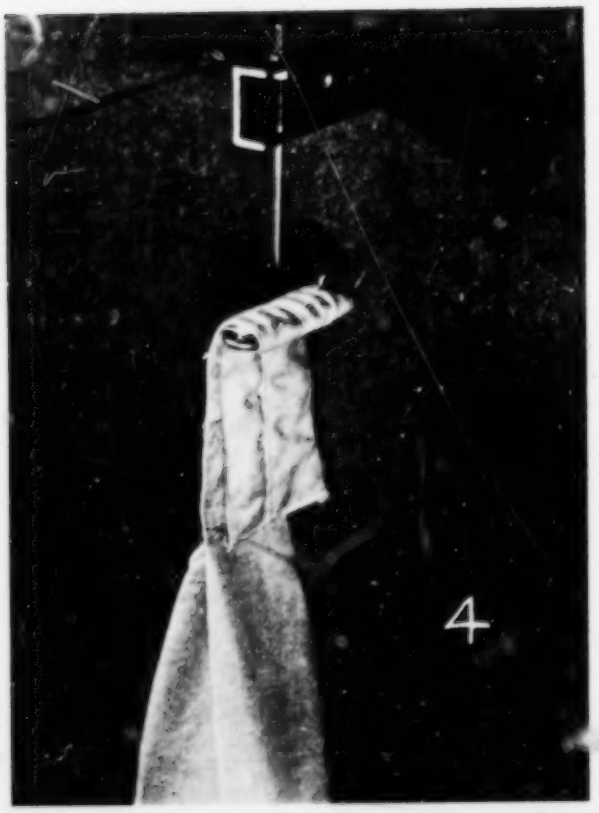
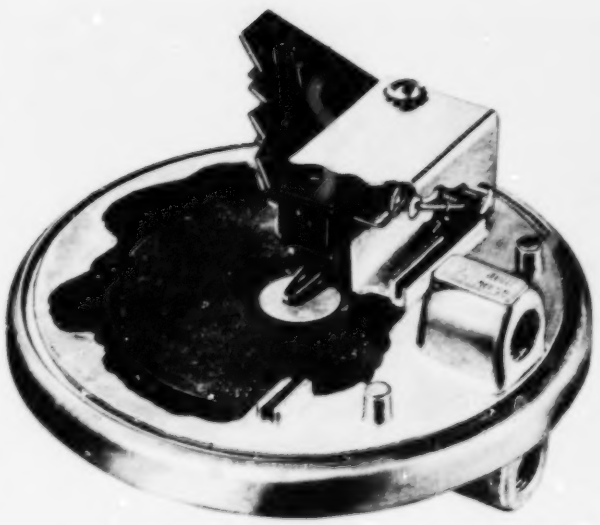


Figure 74. Method of hanging filter bags with strap top: (1) The end of the strap or the tube is brought up between the two horizontal bars of the tube hook. (2) The strap end is folded over the bar, directly under the vertical threaded spindle. (3) The remainder of the strap and the tube proper are brought up and over to the left, with the strap wrapping around the offset horizontal bar of the tube hook, and lying on, or over, the other end of the strap, originally threaded through the hook. The bag, as shown, can be raised, if necessary, by pulling with the right hand on the other end of the strap. (4) The correctly installed tube. Note that the tube proper hangs directly under the vertical threaded spindle of the tube hook (Wheelabrator Corporation, Mishawaka, Ind.).



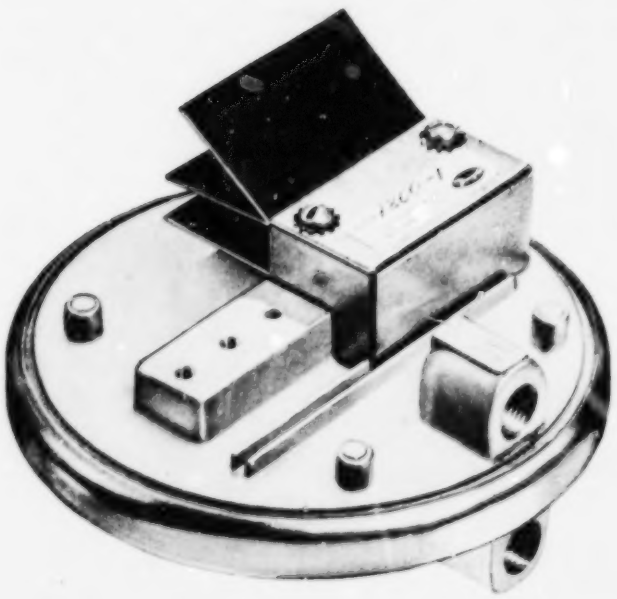


Figure 75. Differential-pressure switch used to control cleaning of bags (F. W. Dwyer Manufacturing Company, Michigan City, Indiana).

od has been found adequate for small baghouses. For larger units, two or more air motor shakers must be used. This cleaning method is economically feasible only when compressed air is already available close to the baghouse.

Pneumatic cylinders are often used for cleaning glass fiber filter bags. This method is used on many of the baghouses serving gray iron cupolas. The pneumatic cylinder gently oscillates the framework from which the bags are suspended. It is frequently used in conjunction with reverse-air collapse of the bags. The amplitude is relatively large and the frequency low.

Bag collapse

Efficiency of cleaning can frequently be improved by permitting a small volume of air to flow in the reverse direction through the bags, causing them to collapse completely. This method is frequently used with glass fiber bags. The bags may be collapsed and reinflated several times for each cleaning. Usually a gentle action is obtained by slowly opening and closing the control valves. Sometimes, however, a stronger cleaning action is required, and the valves are opened and closed quickly so that the bags "snap." Bag collapse may also be used with mechanical shaking, sonic cleaning, or air pulses.

In one variation of this method, several rings are installed on the inside of glass fiber bags. When the air is reversed, the bags collapse inward but the rings prevent the cloth from touching at the center. The flexing of the fabric breaks the filter cake loose. This assertedly permits the cake to fall free without interference. Air pulses are sometimes used for the same reason. During the gentle air reversal, before application of the air pulse, the bags relax and have a tendency towards collapsing. As the short air pulses (generally three pulses of 1 second each) sweep down the filter tube, they create a gentle waving or shaking action, as shown in Figure 76.

Sonic cleaning

Sonic cleaning is relatively new and has not been fully evaluated in the field. It is usually used with bag collapse. The sonic horns employed are relatively expensive, and it is doubtful that the cleaning action is superior to that provided by simple mechanical shaking. In addition, the sound can be extremely annoying unless the baghouse housing is insulated with sound-absorbing materials.

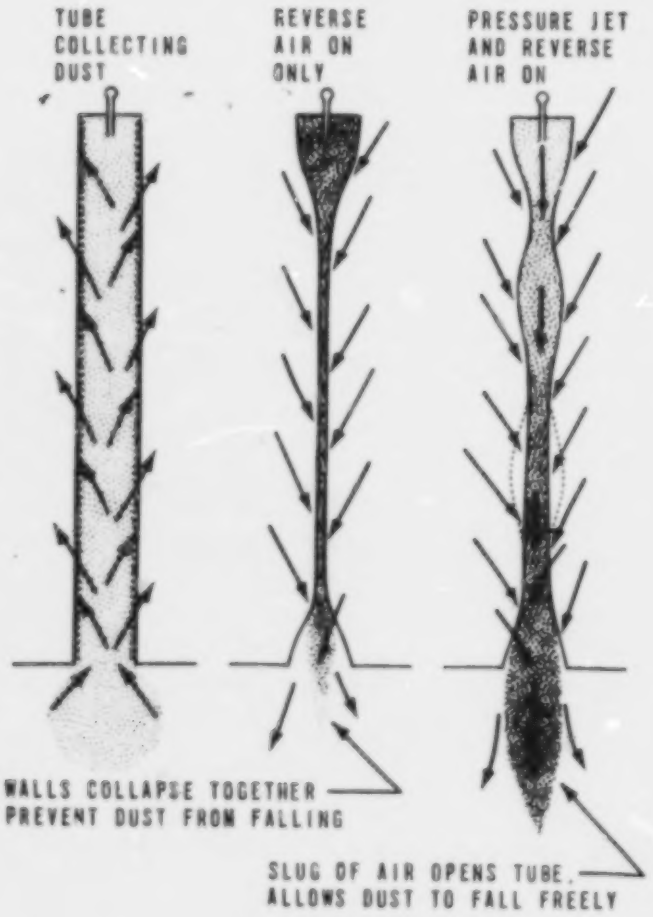

TUBE COLLECTING DUST
REVERSE AIR ON ONLY
PRESSURE JET AND REVERSE AIR ON
WALLS COLLAPSE TOGETHER PREVENT DUST FROM FALLING
SLUG OF AIR OPENS TUBE. ALLOWS DUST TO FALL FREELY

Figure 76. Illustration of method of cleaning bags by collapse and air pulses (Pangborn Corporation, Hagerstown, Indiana).

Reverse airflow

Some envelope-type baghouses use reverse air for cleaning. The dust is collected on the outside of the filtering elements. A moving carriage seals off the outlet of one or several bags at a time. Valves permit outside air to be drawn through the bags in the reverse direction, as shown in Figure 66. This permits continuous cleaning, with only a few bags, at the most, out of service at any time. Sometimes a separate air blower is used to provide the reverse air for cleaning.

Reverse-air jets

Another reverse-air cleaning method is the reverse-jet mechanism developed by Hersey, about 1950. The Hersey-type baghouse, as shown in Figure 67, uses a blow ring that travels up and down the tubular bag. Air for cleaning is blown through a narrow slot on the traveling ring through the filter media in the reverse direction. The filter fabric is also indented or flexed at the point of contact with the ring. The combination of flexing and reverse airflow thoroughly cleans the accumulated dust from the bag. Filter bags are usually made of felted wool cloth. Felted Orlon or Dacron are used for higher temperatures or for better resistance to chemical attack. Woven fabrics are sometimes used, but they usually suffer from reduced collection efficiency because this cleaning method is too thorough. A residual dust cake is essential to the filtering process with woven fabrics. Felted cloths, however, do not require a residual dust mat to filter effectively. The reverse-air jet cleaning method sometimes results in a high rate of wear. Even though reports have been published indicating bag life of several years, experience in Los Angeles County has varied depending upon the application. When this method has been applied to the collection of metallurgical fumes, extremely high rates of bag wear have been experienced. Mechanical breakdowns of the reverse-air mechanisms have also been encountered. All the units installed in Los Angeles County to serve metallurgical operations have been abandoned after a few months of operation or modified to mechanical shaker cleaning. A number of them have, however, been operated successfully for controlling dust from grain transfer and other common dust operations.

There is a tendency to believe that the reverse-jet baghouse may be operated with filtering velocities of about 20 to 30 fpm or even more. This is not generally true, however, as is shown by the Hersey data reproduced in Figure 77. High filter ratios are permissible in special cases only. For example, from curve 9 in Figure 77, a filter ratio of 30 would be permissible for leather-buffing dust (a very coarse material with 30-mesh average size) only if the grain loading were low, not over 3 or 4 grains per cubic foot. For higher grain loadings the filter ratio should be reduced to about 20 cfm per square foot. For metallurgical fumes a maximum filter ratio of about 6 is often recommended, as shown in Table 41. If the grain loading is greater than average or the particle size is small, the filtering velocity should be reduced to 5 fpm or less. These recommendations are confirmed by Hersey's curves, which show that, for very fine dusts and fumes, the limiting filter ratio should be approximately 6 as the grain loading approaches zero. For normal conditions, the filter ratio should be 3 to 5 for metallurgical fumes. Caplan (1960) states that the nature of the dust is the most important variable.

Hersey-type baghouses should logically be operated with filter ratios that bear a fixed relationship to those used with standard shaker-type baghouses. From experience with a variety of medium and coarse dusts, one would expect that

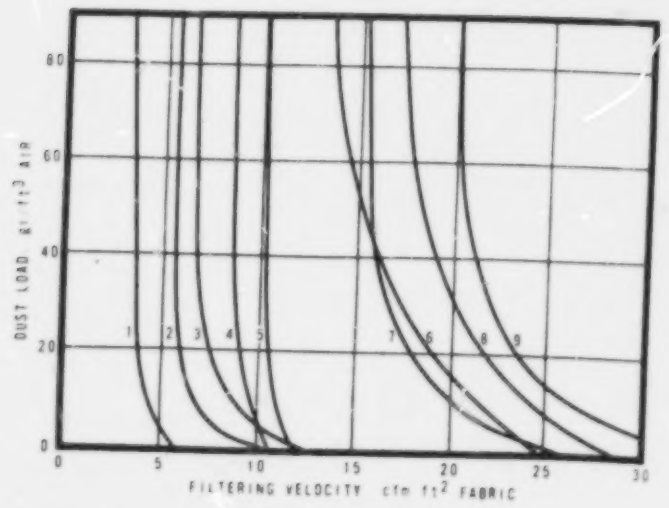


Figure 77. Typical performance of reverse-jet baghouses on a variety of dusts--dust load versus filtering velocity at 3½ inches water column pressure drop (Hersey, 1955). The key to the numbers is as follows: (1) magnesium trisilicate, (2) carbon black, (3) starch dust, (4) resinox, (5) diatomaceous earth, (6) kaolin, (7) cement or limestone dust, (8) coal dust, and (9) leather-buffing dust. For numbers 1 through 6, 99.94 to 99.99% pass 325 mesh; for numbers 7 and 8, 95% pass 200 mesh; number 9 is the 60-mesh average.

reverse-air jet baghouses could be operated with filtering velocities 5 or 6 times as great as those for conventional baghouses. It has been well established that, for most metallurgical dust and fumes, filtration should be 1 to 2 fpm in conventional compartmented baghouses cleaned by shaking, collapse, air pulses, or combinations of these. When metallurgical or other problem dusts and fumes are involved, the design of Hersey baghouses should be more conservative than would be indicated by strictly following any arbitrary rule.

In order to avoid operating difficulties, the pressure drop for a Hersey-type baghouse should usually be in the range of 3 to 5 inches water column (Caplan, 1960). Too low a resistance is undesirable, since it prevents proper inflation of the bag. This results in improper cleaning action. Too high resistance is also undesirable, since it increases the friction between the blow ring and the bag, which increases wear excessively. Hersey-type baghouses should not be operated with pressure drops in excess of 8 inches water column under any circumstances (Caplan, 1960). When the cleaning cycle is pressure controlled, these limits may be used as a guide. If, however, the filtering velocity is excessive, some materials, for example, metallurgical fumes, have a tendency to blind the bags so that even continuous cleaning fails to reduce the pressure as required. When materials such as these are handled, filtering velocities must be reduced. Using the values recommended in Table 41 should provide trouble-free operation in almost all cases. Pilot model studies are useful when previous experience is not available as a basis for determining filter ratio. Sufficient time must be allowed for the pilot unit to reach equilibrium before tests are started. This may require several hundred hours of continuous operation. Failure to allow equilibrium to be attained can result in erroneous data and improper functioning of the full-scale unit designed upon these data.

The speed or rate of travel of the blow ring up and down the bag may be varied according to the nature of the dust being filtered. In general, speeds of from 20 to 50 fpm are employed. The optimum rate of blow ring travel depends upon the nature of the dust. As the blow ring travels, the dust is blown off the inside surface of the bag. This dust will tend to settle at a rate that depends upon the particle size and the specific gravity of the individual particles. It is probably desirable to adjust the blow ring rate of travel so that it does not exceed the settling rate of the dust. A ring speed of approximately 20 fpm has been found optimum for light materials such as grain and flour dust. Speeds of 40 or 50 fpm can be tolerated by high-density dust such as uranium. The volume of air blown through the slot of the blow ring is usually 1.0 to 1.5 cubic feet per linear inch of slot. Slot widths are generally 0.03 to 0.25 inch (Caplan, 1960). Newer designs employ wider slots and centrifugal blowers to provide the reverse air. The original design used a positive-displacement blower. The reverse air must be provided at a pressure greater than the pressure drop through the filter cloth. Furthermore, since higher pressure drops generally indicate finer dusts and fumes, which tend to penetrate the fabric to a greater extent, the differential between the reverse air pressure and the pressure inside the bag probably should be increased somewhat as the pressure drop across the bags increases.

When hot effluents with a high moisture content are handled, it may be necessary to preheat the air used for reverse-jet cleaning. For example, in one case encountered in Los Angeles County, the effluent from a direct-fired dryer was vented to a reverse-jet baghouse. When ambient air was used for cleaning, condensation occurred when the unit was started up early in the morning. After a heat exchanger was installed to preheat the reverse air, the bags remained dry. In some cases a portion of the hot, clean exhaust may be used for reverse-jet cleaning. Care must be taken to remain at least 50°F

Table 41. RECOMMENDED FABRIC AND MAXIMUM FILTERING VELOCITY FOR DUST AND FUME COLLECTION IN REVERSE-JET BAGHOUSES
(American Air Filter Co., Inc., Bulletin No. 279C, Louisville, Ky.)

Material	Fabric	Filtering velocity, fpm
Aluminum oxide	Cotton sateen	9
Bauxite	Cotton sateen	8
Carbon, calcined	Cotton sateen, wool felt	7[a]
Carbon, green	Orlon felt	5
Carbon, banbury mixer	Wool felt	7[a]
Cement, raw	Cotton sateen	7
Cement, finished	Cotton sateen	9
Cement, milling	Cotton sateen	7
Chrome, (ferro) crushing	Cotton sateen	9
Clay, green	Cotton sateen	8
Clay, vitrified silicious	Cotton sateen	10
Enamel, (porcelain)	Cotton sateen	10
Flour	Cotton sateen	10[a]
Grain	Wool felt, cotton sateen	12
Graphite	Wool felt	5[a]
Gypsum	Cotton sateen, Orlon felt	8
Lead oxide fume	Orlon felt, wool felt	6[a]
Lime	Cotton sateen	8
Limestone (crushing)	Cotton sateen	9
Metallurgical fumes	Orlon felt, wool felt	6[a]
Mica	Cotton sateen	9
Paint pigments	Cotton sateen	8
Phenolic molding powders	Cotton sateen	8
Polyvinyl chloride (PVC)	Wool felt	7[a]
Refractory brick sizing (after firing)	Cotton sateen	10
Sand scrubber	Cotton sateen, wool felt	7[a]
Silicon carbide	Cotton sateen	10
Soap and detergent powder	Dacron felt, Orlon felt	9[a]
Soy bean	Cotton sateen	10
Starch	Cotton sateen	8
Sugar	Cotton sateen, wool felt	8[a]
Talc	Cotton sateen	9
Tantalum fluoride	Orlon felt	6[a]
Tobacco	Cotton sateen	9
Wood flour	Cotton sateen	8
Wood sawing	Cotton sateen	9
Zinc, metallic	Orlon felt, Dacron felt	8
Zinc, oxide	Orlon felt	6[a]
Zirconium oxide	Orlon felt	7

[a]Decrease 1 fpm if concentration is great or particle size small.

above the dew point at all times to avoid trouble (Caplan, 1960).

Metallurgical fumes may bleed through the filter bags. In one case where a synthetic felted bag was used, a hard crust formed on the edges of the blow ring slot. This crust rapidly wore out the bags. Substitution of wool felted bags cured the problem. Particle size is not, however, the sole determining factor in leakage. Disturbance of the dust deposit causes some particles to sift through even dense wool felt. Hence, the less reverse-jet activity, the higher the average collection efficiency (Hersey, 1955). Collection efficiency of fly ash (mass median size 16 μ) was found to be less than for either talc (mass median size 2.5 μ) or vaporized silica (mass median size 0.6 μ) (Hersey, 1955), but the reason for this was not determined.

Cleaning Cycles

Manually initiated cycles

Cleaning is most commonly initiated by manually operating the required controls. Electrically or

pneumatically operated shakers are activated by pressing a control button or operating a valve. Interlocks are frequently provided so that the fan or blower must be shut off before the shaking mechanism can be activated. This arrangement is most suitable for operations that may be shut down whenever required for cleaning. It is also suitable when cleaning once or twice a shift is adequate. In such cases, the baghouse is cleaned when the equipment is shut down for lunch or at the end of the shift.

Semiautomatic cycles

Some installations use a semiautomatic cleaning cycle whereby, as the blower is turned off, a timer is activated. After a delay to permit the blower to come to rest, the shaking cycle is initiated. An interlock prevents turning the blower on again before the shaking cycle is completed. This method has been used with success on melting furnaces where a heat does not last more than about 2 hours and the baghouse is adequately sized, so that shaking is not required more than once per heat. At the end of the heat, when there are no emissions from the furnace, the operator presses the button that initiates the cycle. In about 5 or 6 minutes the baghouse has been cleaned and is ready to control emissions from the next heat. While the baghouse is being cleaned, the furnace is empty and no air contaminants are released.

Fully automatic cycles

The most desirable method consists of cleaning a fully automatic, compartmented baghouse on a programmed cycle. The cycle may be initiated at regular intervals or when the pressure reaches a predetermined value. When the cleaning cycle is initiated, one compartment of the baghouse is isolated by means of appropriate dampers. A small volume of reverse air is usually used to ensure collapse of the filter bags. The isolated section is then cleaned by one of the methods previously discussed. After the cleaning cycle is completed, the compartment is again returned to service. Each compartment, in turn, is cleaned in the same manner. The advantage of fully automatic cleaning is that it eliminates the possibility of the operator's forgetting or neglecting to clean the baghouse. Since, however, a greater amount of mechanism is required, the maintenance and the possibility of a breakdown are increased slightly. In many cases, fully automatic cleaning is essential since the basic equipment served cannot be shut down while the baghouse is cleaned. Equipment that operates continuously or requires cleaning during the cycle of operation requires the use of a fully automatic, compartmented baghouse.

Compartmented baghouses must be designed to provide adequate filtering area during all phases of the operation. This means that, when one section of the baghouse is out of service for cleaning, the remaining sections must provide sufficient filtering area. Frequently the design permits two sections to be out of service at one time and still provides sufficient filtering area. This allows one section to be serviced when bags need replacement while the remaining sections continue to operate without exceeding the maximum permissible filtering velocity. Compartmented baghouses are not, however, suitable for very small units. A minimum of five or six compartments is required for efficient operation.

Continuous cleaning

Continuous cleaning is often used in Hersey-type reverse-jet baghouses and in some envelope types. It is suitable for installations that operate with a steady high dust load. If the dust load is variable or light, continuous cleaning will result in unnecessary operation of the carriage and in excessive wear. Pressure control cleaning cycles allow an increase in the resistance of the filter above what the same unit would have for continuous cleaning, as illustrated in Figure 78. The curves show that, for a typical dust concentration of 0.5 grain per cubic foot, operating the cleaning mechanism 30 percent of the time instead of 100 percent results in only a 10 percent increase in filter resistance. If the filtering area of the unit were increased 10 percent, the pressure drop could be expected to be about the same, but the filtering media would last about 3 times as long. While the benefits are not as great for heavier dust loading or fine metallurgical fumes, pressure control cleaning may still be advantageous since the cleaning mechanism need not be operated as much during periods of very light loading.

DISPOSAL OF COLLECTED DUST

Once the dust is collected in a baghouse, it must be disposed of without creating a new dust problem. Occasionally one sees dust dropped on the ground from the collecting hopper of a baghouse. The wind then picks it up and blows it around the neighborhood. The result is substantially the same as if the dust had not been collected in the first place.

The most common means of disposing of the collected dust is to transfer it from the hopper of the baghouse into a truck and then to a dump. In order to minimize dust emissions during transfer from the hopper to the truck, a sleeve or

sock of canvas is frequently installed on the outlet of the hopper. The sleeve should be sufficiently long to reach to the floor of the truck body. The dust must then be thoroughly wetted with water before it is transported to the dump. This method is suitable for installations wherein the quantity of dust collected is such that emptying the hopper once a day is sufficient.

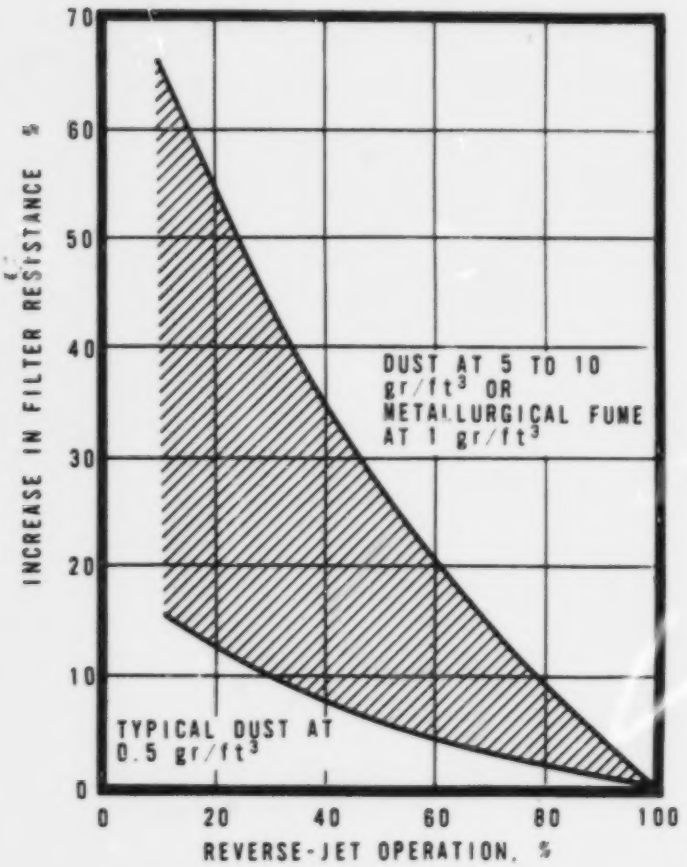


Figure 78. Effect of pressure control on filter resistance in a reverse-jet baghouse (Caplan, 1960).

When the quantity of dust collected is greater, the hoppers must be emptied more frequently. Some type of automatic or semiautomatic method is then advisable. One method consists of using a trickle valve as illustrated in Figure 79. The discharge may be to a completely enclosed tote box. Another method consists of using a rotary valve (Figure 79) that may be operated continuously or intermittently. Both the trickle and the rotary valve may be connected to discharge to a screw conveyor that collects the dust from several hoppers, sometimes even from more than one baghouse, and discharges into a covered tote box or other common collection point.

BAGHOUSE CONSTRUCTION

Pushthrough versus Pullthrough

The blower may be located on either side of the baghouse. If it is on the clean-air side, it is referred to as a pullthrough baghouse. This is desirable since it protects the blower from the dust or fume being handled. On the other hand, it does require a relatively airtight housing for the baghouse. The pushthrough type can be operated with open sides as long as protection from the weather is provided. This is advantageous when handling hot gases, since it permits a greater degree of cooling. Thus, a higher inlet gas temperature may be tolerated for the same temperature of the filtering media. For a pushthrough baghouse, however, the blower must handle the entire dust load. This frequently amounts to several hundred pounds of dust per hour, which may cause substantial wear to the blower. These blowers also require frequent dynamic balancing.

Structural Design

The gage of metal used to construct the baghouse walls, hoppers, and so forth must be adequate, and sufficient bracing must be provided to withstand the loads exerted. A pressure differential of 8 inches water column represents approximately 42 pounds per square foot. The total air pressure exerted on a side panel of a pullthrough baghouse may be in excess of 2 tons. Baghouses have been known to collapse as a result of this air pressure when inadequate bracing was provided. Pullthrough baghouses are more of a problem in this regard than the pushthrough type for two reasons. First, identical baghouse structures can withstand more internal pressure than external pressure without damage. Second, the pressure differential between the inside and outside of the baghouse housing is usually greater for a pullthrough installation than for an otherwise identical pushthrough type.

Hoppers

Size

The size of the hoppers provided must be sufficient to hold the collected dust until it is removed for disposal. If the hopper is emptied once per day, it must be large enough to hold the total amount of dust collected in a full day's operation. Some reserve capacity should also be provided since the quantity of dust may vary from day to day depending upon variations in the basic process. If the hopper does not have adequate capacity, dust already collected becomes reentrained

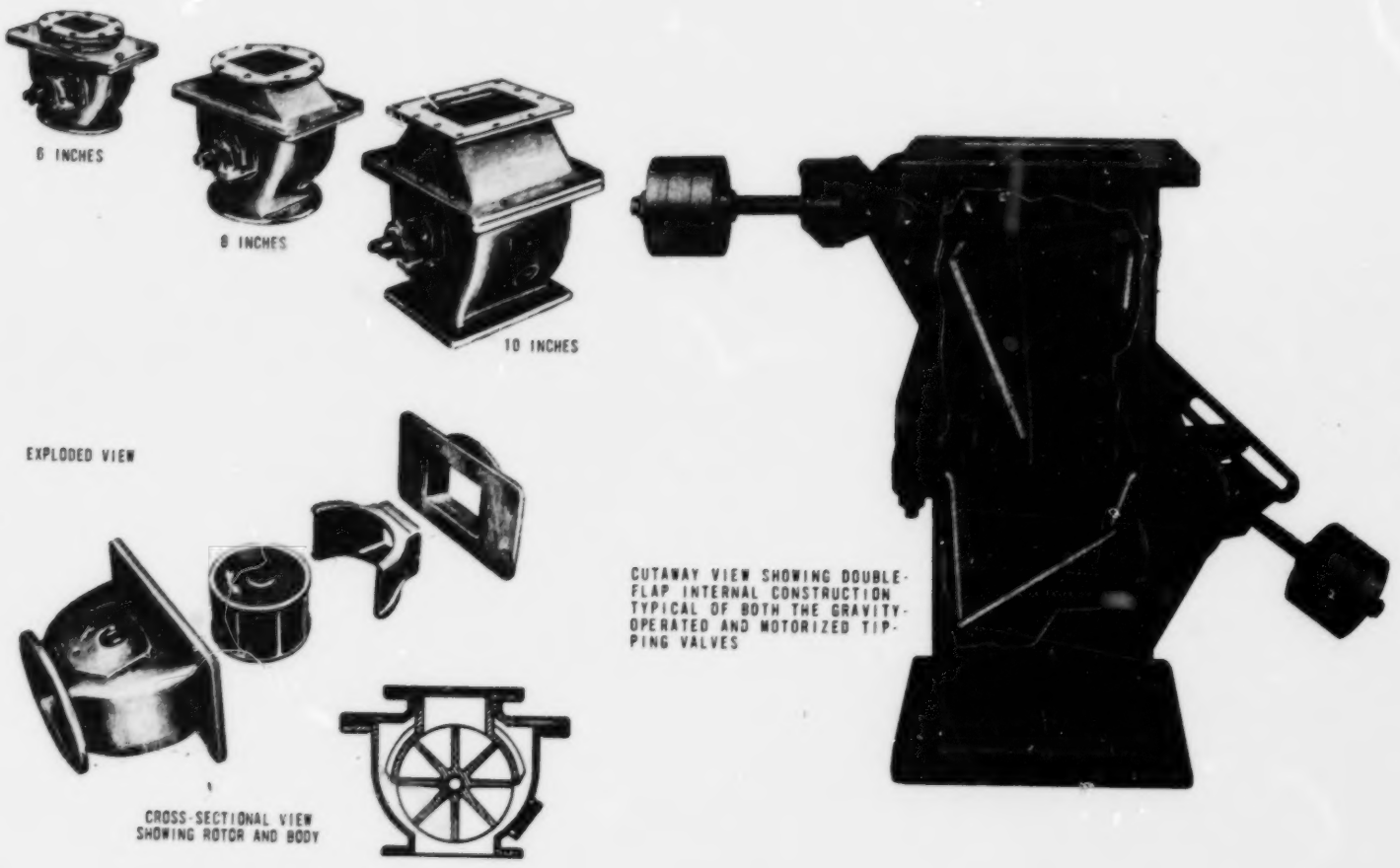

6 INCHES
8 INCHES
10 INCHES
EXPLODED VIEW
CROSS-SECTIONAL VIEW SHOWING ROTOR AND BODY
CUTAWAY VIEW SHOWING DOUBLE-FLAP INTERNAL CONSTRUCTION TYPICAL OF BOTH THE GRAVITY-OPERATED AND MOTORIZED TIPPING VALVES

Figure 79. Hopper discharge valves (Western Precipitation Corporation, Division of Joy Manufacturing Co., Los Angeles, California).

increasing the total dust load on the filter cloth and thereby the filter resistance. This is detrimental to the performance of the baghouse. Deflectors are often installed to minimize or prevent this reentrainment to some extent.

Slope of hopper sides

The slope of the sides of the hopper must be sufficient to permit the dust to slide or flow freely. The design must also consider the possibility of bridging. Continuous emptying of hoppers will help to prevent bridging of material that has a strong tendency to do so. It will also prevent operating difficulties with materials that tend to become less fluid with time. For example, some materials have a tendency to cake if permitted to stand for a few hours or overnight. This is especially true of hygroscopic materials that absorb moisture from the air.

Gage of metal

The gage of metal required for constructing hoppers depends upon the size of the hopper and the service. For small hoppers and light duty, 16-gage metal may be used. The gage should be increased as warranted by the size of the hopper and the total weight of the dust to be held at any one time. In addition, however, consideration should be given to the fact that workers frequently hammer on the sides of hoppers to assist the collected dust to flow freely from the discharge gate. If materials tend to stick or cake or are not freely flowing, some hammering on the sides of the hoppers will certainly result. Many hoppers have been badly dented as a result of rough treatment.

Use of vibrators and rappers

A much better solution than hammering on the sides of the hoppers is to provide mechanical rappers or vibrators. The most frequently used device is the electrically operated Syntron vibrator. Air-operated vibrators are also used extensively. A rapping device is highly desirable when a rotary discharge valve or screw conveyor is used. The rapper may be operated from a cam attached to the shaft of the rotary valve. In some cases the valve, rapper, and screw are all operated from a single electric motor.

Discharge

Many baghouses, especially small, simple ones, use a slide gate at the bottom of the hopper to control the discharge of the collected dust from the hopper. Other valves commonly used are shown in Figure 79. The rotary valve is usually used on fully automatic units. The operation of the gravity trickle valve may be affected by the pressure in the baghouse.

MAINTENANCE

Service

Every mechanical device, no matter how well designed and constructed, must be serviced periodically if it is to continue to operate properly. A baghouse, even the simplest, is no exception to this rule. Maintenance is usually adequate when the collected dust has sufficient economic value. The self-interest of the operator then requires that the equipment be kept in optimum operating condition. In many cases, however, baghouses are installed because local air pollution regulations require it. When the baghouse is nonproductive, the operator has little motivation to maintain it in optimum condition; however, this is a foolish and shortsighted attitude. Unless the baghouse is properly maintained, the investment, large or small, is wasted. In many cases the additional expense required to recondition equipment, which has long been neglected, is as much or more than the expense of continually maintaining the equipment in optimum condition would have been.

A proper maintenance program requires establishing a schedule for the various operations that must be performed periodically. The hoppers should be emptied and the collected dust disposed of at least once a day. Depending upon the nature of the dust, the quantity collected, and the general severity of the service, the equipment should be thoroughly inspected at intervals of a week, a month, or quarterly. Moving parts such as the shaking mechanisms must be greased and oiled at intervals specified by the manufacturer. For baghouses in daily use, all bags should be examined at least once a week to determine whether any are showing wear. Bags having holes or rips should be replaced immediately. Frequently, trouble can be detected before it becomes fullblown. Large baghouses benefit by the maintenance of a chart on which the history of each bag is recorded. If bags in one area show a history of more frequent replacement than those in other areas, this should be investigated.

Bag Replacement

Some operators find it more economical to replace all the bags periodically before serious trouble begins to develop. For example, one operator in the Los Angeles area replaces all the bags in a quarter of the baghouse every 3 months. Thus, every bag is replaced once a year. A thorough inspection is, moreover, made monthly. If an individual bag develops a hole or a rip or shows any sign of wear, it is replaced when detected. The advantage of this maintenance schedule is that the overall cost may be lower compared with replacing bags only when they fail. In this particular case, experience with other, similar equipment indicates that bag failures generally occur between 1 and 2 years after installation, with an average life of 18 months. Thus, after a year, frequent replacements would be required. The labor required to replace a bag when one bag is replaced at a time can be estimated to be approximately 1/2 to 1 man-hour. If an entire section (375 bags) is replaced at one time, the greater efficiency reduces the labor required to about 0.086 man-hour per bag. In either case, the cost of the bag itself is about $10. While the labor and material cost of group replacement is not necessarily less, there are many other advantages. The baghouse in this illustration serves a furnace operated 24 hours per day, 7 days per week. When a bag failure occurs, the baghouse must be shut down while the bag is replaced. This means that the furnace must shut down or a citation will be received for excessive emissions. Obviously, lost production time is expensive. When group replacement is used, service is scheduled to coincide with furnace shutdown for relining without loss of production.

Each operator must decide which method is best in respect to his own operating experience, the anticipated bag life, and the material and labor cost. Also to be considered is whether or not the equipment can easily be shut down when trouble develops.

Replacement of one or several bags in a large baghouse is not usually desirable though it is sometimes unavoidable if an individual bag becomes defective. In this case, the resistance of the new bags during the initial startup will be very low compared with that of the older bags. As a result, the filtering velocity through the new bags will be many times in excess of the normal rate. This could result in blinding of a new bag during the first few minutes of operation. It would be desirable to take the precaution of returning the equipment to service gradually in such cases, but baghouses are not normally designed and constructed in a manner that permits this to be done.

Precoating

One solution to the problem of high filtering velocities for new bags would be to precoat the bags with dust to establish a cake immediately after installation. Precoating is a very desirable procedure, and some authorities have recommended that all bags should be precoated immediately after each cleaning cycle. It has also been recommended that compartmented baghouses have automatic programming equipment so that each section, after cleaning, is precoated before it is returned to service. This was done in one case by installing a cyclone precleaner. The coarse dust collected by the cyclone was then automatically introduced into the airstream immediately after each cleaning cycle.

Precoating with a relatively coarse dust is especially beneficial when a fine fume is being filtered (Drinker and Hatch, 1954). The precoat ensures a high efficiency immediately after the bags are cleaned, increases the capacity of the unit, and decreases the pressure loss. In many cases the additional expense of equipment for automatically precoating the bags would be repaid in additional usable life of the filter media, improved collection efficiency, and reduced draft loss.

The design of some simple baghouses may unintentionally result in automatically precoating the bags each time the unit is started. The inlet duct usually enters the baghouse through the dust-collecting hopper. At startup, some of the previously collected dust in the hopper is disturbed and serves as a precoat on the filter bags. Since the collected dust is usually agglomerated into relatively coarse particles, it is an effective precoat material. If, however, an excessive quantity of dust is deposited upon the filter media, the capacity of the unit is reduced and the resistance is increased unnecessarily.

SINGLE-STAGE ELECTRICAL PRECIPITATORS

Electrical precipitation is frequently called the Cottrell process for Frederick Gardner Cottrell (1877 to 1948), who designed and built the first successful commercial precipitator. It is defined as the use of an electrostatic field for precipitating or removing solid or liquid particles from a gas in which the particles are carried in suspension. The equipment used for this process is called a precipitator or treater in the United States. In Europe it is called an electrofilter. A precipitator installation is shown in Figure 80.

HISTORY OF ELECTROSTATIC PRECIPITATION

Origins of Electrostatic Principles

The first recorded reference to the phenomenon of electrostatic attraction, which forms the basis for the precipitating action in an electrical precipitator, is attributed (Priestley, 1958) to Thales of Miletus about 600 B. C. He noted that a piece of amber that has been rubbed attracts small, light fibers. The word electricity came from elektron, the Greek word for amber. Pliny wrote of the attraction of chaff and other light objects to the amber spindles of wheels in Syria.

It was not until William Gilbert published his historical De Magnete in the year 1600 that serious progress toward understanding electrical and electrostatic phenomena commenced. Gilbert compiled a list of "electrics," materials possessing the property of attraction when rubbed, and "nonelectrics," materials not having this property. In 1732 Stephen Gray succeeded in demonstrating that the so-called nonelectrics could be given an electrical charge if they were properly insulated. Since some materials could be charged positively and others negatively, two different types of electricity were postulated. In 1754 John Canton demonstrated that materials could be charged either positively or negatively, leading to the development of the single-fluid theory of electricity proposed by Benjamin Franklin.

In 1832 Faraday proposed an atomic theory of electricity. Faraday's theory resembled both the one-fluid and two-fluid theories. He assumed two kinds of charged particles, which we now call protons and electrons. He assumed that only the negative particles (electrons) could be transferred from one body to another.

Although the fact that charged particles attract or repel each other, depending upon whether the charges are unlike or like, had been known for some time, it was not until Coulomb devised a torsion balance of sufficient sensitivity that the relationship between the charge, separation, and force was determined. Coulomb demonstrated that the force of attraction or repulsion between two static charges is proportional to the product of the charges and inversely proportional to the square of the distance between them, as expressed in equation 53:

$$F = \frac{q_1 q_2}{D S^2} \qquad (53)$$

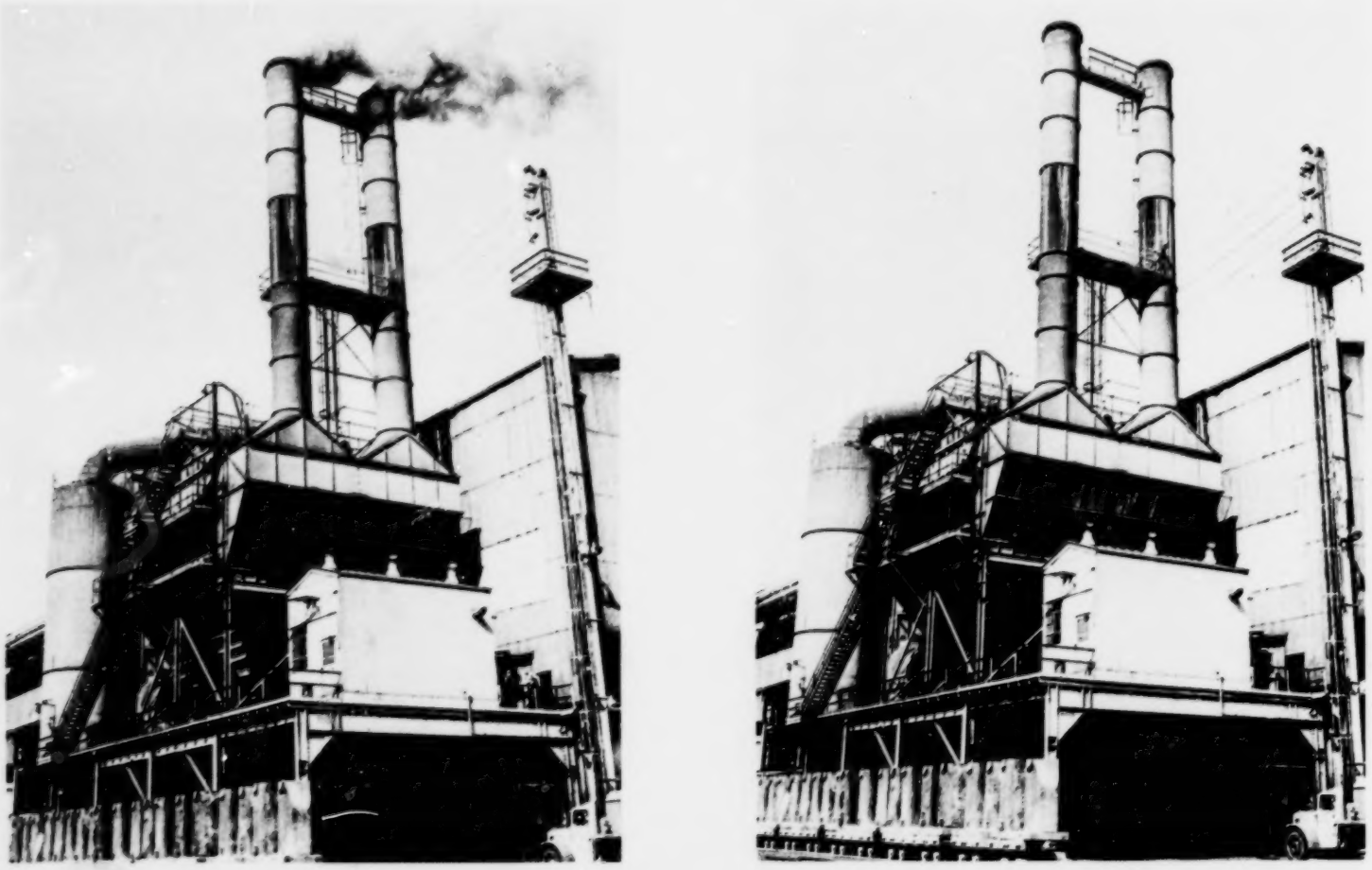


Figure 80. An electrical precipitator controlling the emissions from a 75-ton and a 50-ton electric-arc steel-melting furnace (left) precipitator off, (right) precipitator on (Bethlehem Steel Co., Los Angeles, Calif.).

where

F = force of attraction or repulsion between two particles, dynes

q_1, q_2 = charge on particles, statcoulombs

D = dielectric constant of medium between the particles, dimensionless

S = distance between the particles, cm.

In a vacuum, for which the dielectric constant $D = 1$, if the force is 1 dyne and the distance between the (equal) charges is 1 centimeter, the fundamental electrostatic unit of charge is defined. Called a statcoulomb, it is the charge associated with approximately 2.08×10^9 electrons.

The forces exerted by electrical charges are dependent upon the medium through which they are exerted. Thus, the force as defined by Coulomb's law depends upon D, the dielectric constant of the medium. Values of the dielectric constant for a number of common materials are given in Table 42. The dielectric constant may be taken, with negligible error, as unity for air at normal temperature and pressure.

In order to explain the phenomenon of attraction and repulsion between charges, a hypothetical electric field is postulated. The strength of an electric field at any point may be expressed as the quotient of the force exerted on a test charge placed at that point divided by the magnitude of the charge. It must be assumed, of course, that introducing a charge into an electric field does not alter the field, which is a reasonable assumption only if the charge is very small compared with the strength of the field. Field strength may also be expressed as the potential difference divided by the distance. Equation 54, defines the strength of a uniform electric field:

$$E = \frac{F}{q} = \frac{V_o}{S} \qquad (54)$$

where

E = field strength or electrostatic potential gradient, statvolt/cm

V_o = electrostatic potential difference, statvolt.

Table 42. DIELECTRIC CONSTANTS FOR SOME COMMON MATERIALS

Material	Dielectric constant[a]
Air	1.0006
Alumina	4.50 to 8.40
Ammonium chloride	7
Calcium carbonate	6.14
Dolomite	6.80 to 8
Ferrous oxide	14.20
Glass (pyrex)	3.80 to 6
Quartz (fused)	3.75 to 4.10
Sodium chloride	6.12
Steam	1.01
Sulfur	4
Titanium dioxide	14 to 110
Water	80

[a]These values vary with the temperature, humidity, pressure, and electrical frequency at which measured.

Early Experiments With Electrostatics on Air Contaminants

In 1824, Hohlfeld performed an experiment in which he succeeded in clearing the air in a jar of fog by means of an electrified point. Guitard performed a similar experiment in 1850 in which tobacco smoke was cleared from the air in a glass cylinder 9 inches in diameter by 18 inches long. These experiments were forgotten until Sir Oliver Lodge uncovered them in 1905, more than 20 years after he had independently demonstrated the same phenomenon. Information in this field was also published by Gaugain in 1862 on the disruptive discharge between concentric cylindrical electrodes, and by Nahrwold, who, in 1878, found that the electric discharge from a sharp point in a tin cylinder greatly increased the rate of settling or collection of atmospheric dust. To make the collected particles adhere, he coated the walls of the cylinder with glycerin (White, 1957).

The first attempt to use the principles of electrical precipitation commercially was made by Walker and Hutchings at a lead smelter works at Baggilt, North Wales, in 1885. They were inspired by the early work of Sir Oliver Lodge in this field. This first attempt was not successful, partly because lead fume is one of the most difficult materials to collect by electrical precipitation and partly because they were unable to provide an adequate power supply with their crude equipment (White, 1957).

Development of the First Successful Precipitator

The first successful commercial use of electrical precipitation was developed by Cottrell in 1907 (Cameron, 1952). Cottrell, while an instructor at the University of California at Berkeley, was approached by the management of the recently constructed Du Pont Explosives and Acids Manufacturing Plant near Pinole, California, about 12 miles north of Berkeley on San Pablo Bay. This plant was using the then new Mannheim process or "contact" method in place of the chamber process to manufacture sulfuric acid. In the contact process, sulfur dioxide and oxygen are passed through an iron oxide catalyst to form sulfur trioxide from which the sulfuric acid is made. Difficulty was experienced owing to arsenic, which was poisoning the catalyst. Cottrell first attempted a solution to the problem by means of collecting the acid mist with a laboratory model centrifuge. Although the centrifuge principle was moderately successful in the laboratory, the first pilot plant model tried at Pinole was a failure. Before Cottrell was able to proceed further with this work, all his notes and models were destroyed in the fire that accompanied the San Francisco earthquake of 1906. Discouraged but undaunted, Cottrell rejected an appointment to head the Chemistry Department at the Texas Agricultural and Mechanical College in order to follow up an idea of collecting the acid mist by electrical precipitation.

After demonstrating that electrical precipitation would collect smoke, Cottrell made a small contact acid plant and passed the sulfuric acid mist into a round glass jar. Inside the jar was a cylinder of wire screening around which was wrapped several turns of asbestos-wrapped sewing twine. The walls of the jar became the collecting electrode. Three factors contributed to the ultimate success of his first electrostatic precipitator. The first was the use of a pubescent electrode. He also discovered that the use of negative polarity resulted in a more stable and efficient operation. The third factor was his use of rectified alternating current. For this purpose, he developed a mechanical rectifier. With financial backing from friends, Cottrell organized two corporations and constructed a pilot collector that handled 100 to 200 cubic feet of gas per minute. This pilot unit was installed at Pinole where it operated satisfactorily, handling a gas current representing about 3 tons of sulfuric acid per day and consuming less than 1/3 kilowatt. The apparatus is shown in Figure 81, taken from Cottrell's 1908 patent.

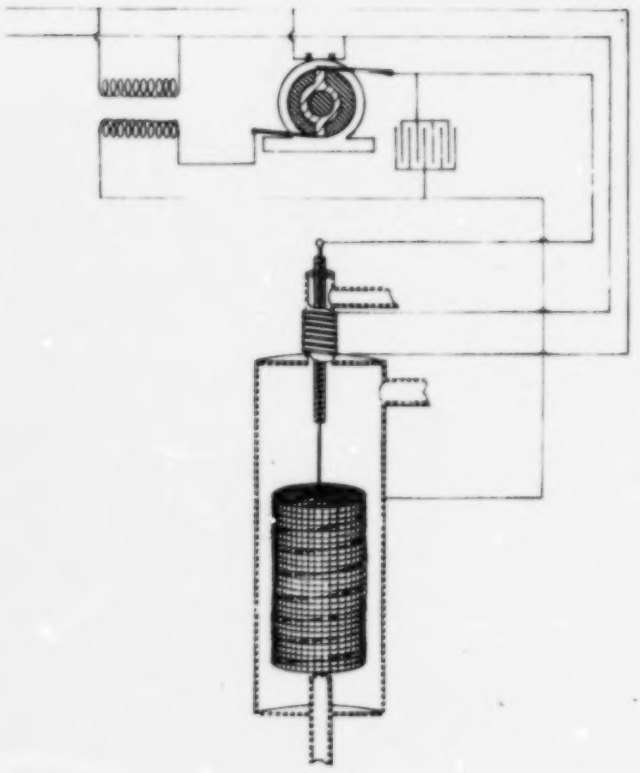


Figure 81. Illustration from Cottrell's first (1908) electrostatic precipitation patent, No. 895,729 (Research Cottrell, Bound Book, N. J.).

Improvements in Design, and Acceptance by Industry

After Cottrell proved that electrical precipitation could be applied successfully to the collection of industrial air contaminants, the use of electrical precipitation expanded into many diverse fields. Table 43 lists some of the pioneer installations.

Table 44 summarizes the extent of the use of electrical precipitation in the United States only 50 years after Cottrell first succeeded in demonstrating the practicality of this principle for the control of industrial air contaminants. Table 45 lists data that typify installations of modern electrical precipitators. Obviously, precipitators serve for a variety of industrial applications, sizes, dust concentrations, particle sizes, and efficiencies.

ADVANTAGES AND DISADVANTAGES OF ELECTRICAL PRECIPITATION

The use of electrical precipitators for the collection of air contaminants has grown because of many inherent advantages, some of which are now listed.

1. High efficiency can be attained. Efficiency may exceed 99 percent in some cases.

2. Very small particles can be collected. There is no theoretical lower limit to the size of a particle that can be collected.

3. Dusts may be collected dry for recovery of valuable material.

4. Pressure and temperature drops are small. The pressure drop through an electrical precipitator seldom exceeds 0.5 inch vertical water column.

5. Precipitators are normally designed to operate continuously with little maintenance over long periods of time.

6. There are very few, if any, moving parts, which tends to reduce the maintenance required.

7. Precipitators can be used at high temperatures. Temperatures up to about 700°F are normal. Special designs have been used for temperatures as high as 1,300°F, but ordinarily the temperature does not exceed 1,000°F (Sproull, 1951).

8. Precipitators can be used to collect acid and tar mists, which are difficult, if not impossible, to collect by other methods.

9. Extremely corrosive materials can be collected with special construction.

10. Collection efficiency may be adjusted to suit the application by increasing the unit size.

11. Very large gas flow rates can be handled.

12. The power requirements for flow handled are low. For example, the actual power required to clean 500,000 cubic feet of gas per minute at 95 percent efficiency, including the draft loss, is only about 65 kilowatts (White, 1953).

Electrical precipitators are by no means a panacea for air pollution problems. In many cases, disadvantages far outweigh the advantages. Some of the drawbacks are now listed.

1. Initial cost is high. In most cases the investment is greater than that required for any other form of air pollution control.

2. Precipitators are not easily adaptable to variable conditions. Automatic voltage control helps to a great extent, but precipitators are most efficient when operating conditions remain constant.

3. Some materials are extremely difficult to collect in an electrical precipitator because of extremely high or low resistivity or other causes. In some cases, this factor alone makes the use of electrical precipitation uneconomical, if not physically impossible.

4. Space requirements may sometimes be greater than those for a baghouse. In general, this is true only when high collection efficiency is required for materials difficult to collect by precipitation.

5. Electrical precipitation is not applicable to the removal of materials in the gaseous phase.

6. The use of a precleaner, generally of the cyclonic type, may be required to reduce the dust load on a precipitator.

7. Special precautions are required to safeguard personnel from the high voltage.

Table 43. PIONEER PRECIPITATOR INSTALLATIONS, 1907 to 1920 (White, 1957)

Application	Date	Location
Sulfuric acid mist from contact acid plant, 200 cfm	1907	Pinole, Calif.
Smelter, zinc and lead fumes, 300,000 cfm	1910	Shasta Co., Calif., Balaklala
Cement kiln dust, 1 million cfm	1912	Riverside, Calif.
Copper converter (lead fume), 200,000 cfm	1912	Garfield, Utah, American Smelting and Refining Co.
Gold and silver recovery from furnace treatment of electrolytic copper slimes	1913	Perth Amboy, N.J., Raritan Copper Works
Absorption of chlorine gas by powdered lime followed by precipitator collection	1913	Niagara Falls, N.Y., Hooker Electro-Chemical
Dwight-Lloyd sintering machine lead fume, 20,000 cfm	1914	Tooele, Utah, International Smelting and Refining Co.
Tar removal from illuminating gas, 25,000 cfm	1915	Portland, Oregon
Cleaning ventilating air in factory; air not recirculated, 55,000 cfm	1915	New Haven, Conn., Winchester Arms
Paper pulp recovery of alkali salts from waste liquor evaporated gases, 90,000 cfm	1916	Canada
Central gas cleaning plant, 2 million cfm	1919	Anaconda, Mont., Anaconda Copper Smelting Co.

Table 44. SUMMARY OF UNITED STATES PRECIPITATOR INSTALLATIONS IN MAJOR FIELDS OF APPLICATION, 1907 to 1957 (White, 1957)

Application	First installation	Number of precipitators	Gas flow, million cfm	
Electrical power industry: (fly ash)	1923	730		157
Metallurgical:				43.4
Copper, lead, and zinc	1910	200	15	
Steel industry	1919	312	22.5	
Aluminum smelters	1949	88	5.9	
Cement industry:	1911	215		29
Paper mills:	1916	160		18
Chemical industry:	1907	500		9
Detarring of fuel gas:	1915	600		4.5
Carbon black:	1926	50		3.3
Total		2,855		264.2

The decision whether to use an electrical precipitator, a baghouse, or some other type of collector must be made after considering all the following factors:

1. Initial investment;

2. maintenance, including the cost of power to operate the device;

3. space requirements;

4. collection efficiency, which must be evaluated in terms of the value of the collected material or restrictions placed on the discharge of air contaminants by local regulations, or both (sometimes good public relations require an even higher collection efficiency than can be justified solely on the basis of economics).

The cost of providing high efficiency is illustrated by the fact that the cost nearly doubles when electrical precipitator collection efficiency is increased from 80 to 96 percent and almost triples from 80 to 99 percent.

MECHANISMS INVOLVED IN ELECTRICAL PRECIPITATION

The process of electrostatic precipitation consists of a number of elements or mechanisms, which are now listed.

1. Gas ions are formed by means of high-voltage corona discharge.

2. The solid or liquid particles are charged by bombardment by the gaseous ions or electrons.

3. The electrostatic field causes the charged particles to migrate to a collecting electrode of opposite polarity.

4. The charge on a particle must be neutralized by the collecting electrode.

Table 45. TYPICAL DATA ON ELECTRICAL PRECIPITATOR APPLICATIONS
(Air Pollution Handbook, 1956)

Industry	Application	Gas flow range, cfm	Temp range, °F	Dust concentration range, grains/ft^3	Weight % of dust below 10 μ	Usual efficiency, %	Cost range,[a,b] $/cfm
Electric power	Fly ash-pulverized coal-fired boilers	50,000 to 750,000	270 to 600	0.40 to 5	25 to 75	95 to 98	0.50 to 0.85
Portland cement	Dust from kilns	50,000 to 1 million	300 to 750	0.50 to 15	35 to 75	85 to 99+	1 to 1.50
	Dust from dryers	30,000 to 100,000	125 to 350	1 to 15	10 to 60	95 to 99	0.60 to 1
	Mill ventilation	2,000 to 10,000	50 to 125	5 to 25	35 to 75	95 to 99	1.50 to 3
Steel	Cleaning blast furnace gas for fuel	20,000 to 100,000	100 to 150	0.02 to 0.5	100	95 to 99	2 to 3
	Collecting tars from coke-oven gases	50,000 to 200,000	100 to 150	0.10 to 1	100	95 to 99	0.75 to 1.75
	Collecting fume from open-hearth and electric furnaces	30,000 to 75,000	300 to 700	0.05 to 3	95	90 to 99	1 to 3
Nonferrous metals	Fume from kilns, roasters, sintering machines, aluminum pot lines, etc.	5,000 to 1 million	150 to 1,100	0.05 to 50	10 to 100	90 to 98	2 to 10
	Acid mist	See chemical industry					
Pulp and paper	Soda-fume recovery in kraft pulp mills	50,000 to 200,000	275 to 350	0.50 to 2	99	90 to 95	1 to 2.50
	Acid mist	See chemical industry					
Chemical	Acid mist	2,500 to 20,000	100 to 200	0.02 to 1	100	95 to 99	2 to 3.50
	Cleaning hydrogen, CO_2, SO_2, etc.	5,000 to 20,000	70 to 200	0.01 to 1	100	90 to 99	1.50 to 5
	Separate dust from vaporized phosphorus	2,500 to 7,500	500 to 600	0.01 to 1	30 to 85	99+	5 to 10
Petroleum	Powdered catalyst recovery	50,000 to 150,000	350 to 550	0.10 to 25	50 to 75	99 to 99.9	1.50 to 2.50
Rock products	Roofing, magnesite, dolomite, etc.	5,000 to 200,000	100 to 700	0.50 to 25	30 to 45	90 to 98	1.50 to 10
Gas	Tar from gas	2,000 to 50,000	50 to 150	0.01 to 0.2	100	90 to 98	1 to 1.75
Carbon black	Collecting and agglomerating carbon black	20,000 to 150,000	300 to 700	0.03 to 0.5	100	10 to 35[c]	0.75 to 1.50
Gypsum	Dust from kettles, conveyors, etc.	5,000 to 20,000	250 to 350	1.50 to 5	95	90 to 98	2.10 to 3.50

[a] The lower figures apply to the larger volumes and lower efficiencies, and the upper figures apply to the smaller volumes and higher efficiencies.

[b] Installed, based on 1955 cost. Actual cost may be increased substantially if unusual problems must be surmounted.

[c] The precipitator serves primarily to agglomerate the particles. Most of the collection occurs in the cyclone that follows the precipitator.

5. Reentrainment of the collected particles must be prevented.

6. The collected particles must be transferred from the collecting electrode to storage for subsequent disposal.

The accomplishment of these functions by an electrical precipitator has required the development of many specialized techniques for specific materials, though the broad principles remain as enumerated.

DIVERSE APPLICATIONS OF ELECTRICAL PRECIPITATION

Table 46 illustrates the broad spectrum of materials that are collected by electrical precipitation and the range of dust concentrations that may be encountered in practice.

Dispersoids in gases may be a one-component system, but two or more components are usual in industrial air pollution control. The dispersed phase may be a liquid, as in clouds, mists, or in sprays, or may be a solid, as in a dust cloud or metallurgical fume. Dispersed systems include dusts, fogs, clouds, mists, hazes, fumes, or smokes.

In general, the size of dust particles varies from 5 to 100 microns and fumes vary from 0.1 to 5 microns. Table 47 lists typical particle sizes encountered in industrial dusts and fumes.

Construction Details of Electrical Precipitators

Essential features of precipitator design, exemplified in Figure 82, include the following elements: Rappers, shell, cable from rectifier, support frame, corona wires, collecting plates, gas inlet, hoppers, wire-tensioning weights, and hopper baffles.

Discharge electrodes

The discharge electrodes provide the corona, without which the precipitator cannot function. These may be round wire, square twisted rods, ribbons, barbed wire, and so forth. Steel alloys are commonly used, but other materials that have been used include stainless steel, fine silver, nichrome, aluminum, copper, hastelloy, lead-covered steel wire, and titanium alloy. While the choice of material is usually dictated by the requirements of corrosion resistance, the physical configuration must be determined to meet the electrical characteristics requirements. When round wires are used, the diameter is usually about 3/32 inch, though it may vary from about 1/16 to 1/8 inch. Conventionally, 3/16-inch-square twisted wire has been used for precipitators serving catalytic cracking units. The use of barbs and various special shapes is strongly advocated by some authorities, but others equally competent dispute these claims, pointing out that no decided advantage has ever been established for the use of special discharge electrodes.

Collecting electrodes

The variety of collecting electrodes available is even more diverse. Materials of construction and special shapes appear to be limited only by the imagination of the designer. While many of these special shapes have important advantages, the use of smooth plates, with fins to strengthen them and produce quiescent zones, has become most common in recent years. The preference between one special shape and another frequently becomes one of conjecture. Figure 83 illustrates some of the special collecting electrode configurations marketed. These include perforated or expanded plates, rod curtains, and various hollow electrodes with pocket arrangements on the outside surfaces for conducting the precipitated dust to the hopper in quiescent gas zones. Concrete plates were used at one time but were abandoned about 1930 because of excessive cost and weight. Smooth transite plates are used occasionally because of their excellent corrosion resistance. These are, however, for unusual cases, because of the severe reentrainment problem. For fly ash, perforated or expanded metal plates provide a multiplicity of closely spaced holes that hold the ash while end baffles on the plates shield the perforated surfaces from the direct scouring action of the gas. Several variations of the V electrode have also been used and have similar characteristics. The hollow or pocket-type electrodes are attractive in principle, but in practice, a large proportion of the dust actually falls on the outside of the plates. Furthermore, much of the dust collected in the upper openings actually escapes to the outside through the lower openings because of the piston action of the falling dust (White, 1953).

Tubular collecting electrodes

Plate-type precipitators are usually preferred because they can handle a larger volume of gas in a smaller space for less investment than the tube type. The tube type, often called "pipe type," lends itself more readily, however, to wet collection and is, therefore, preferred for acid mists and tars. In the case of detarring precipitators, the tar collects on the inside walls of the tubes and runs by gravity to col-

Table 46. CONCENTRATIONS OF SUSPENDED MATTER IN COMMERCIAL GASES IN TYPICAL ELECTRICAL PRECIPITATOR INSTALLATIONS (Kirk and Othmer, 1947)

	Concentrations, grains/ft^3 of gas, STP
Acid mist--sulfuric acid (contact plant)	
After roaster	
Multiple-hearth roaster--zinc and pyrites	1.08 to 5.80
Flash roaster--zinc blend	0.00475 to 0.05550
After absorbers--tail gases	0.722 to 2.310
Acid mist--phosphoric acid--from burning phosphorus (basis 100% H_3PO_4)	48.3 to 66.2
Assay offices and mines--ventilating gases from furnaces and assay operations	0.0028 to 0.0515
Carbon black	
From cracking natural gas	5.1 to 17
From oil cracking	19 to 40
Carbureted water gas	
Dry-tar basis	0.755 to 1.590
Wet-tar basis	1.08 to 2.26
Catalytic cracking units--oil	
Atmospheric-pressure units--after mechanical collector	
Natural catalyst	19.45 to 85.60
Synthetic catalyst	16.5 to 52.9
High-pressure units--after mechanical collector	
Natural catalyst	7.19 to 22.75
Synthetic catalyst	4.69 to 94.60
Cement-kiln gases (wet process)--dust concentrate entering stack	
Wet-gas basis	2.62 to 3.80
Dry-gas basis	3.34 to 4.68
Coke-fired producer gas	0.03 to 0.06
Coke-oven gas	
Ahead of exhausters, dry-tar basis	4.51 to 4.88
After positive-displacement exhausters, wet-tar basis	3.14 to 4.58
After centrifugal exhauster, wet-tar basis	1.66 to 3.74
Fly ash from boilers burning pulverized soft coal	1 to 5
Gypsum-plant gas	
From rotary calciners, wet-gas basis	32.82 to 48.07
From dryers, wet-gas basis	64.52
From gypsum kettles, dry-gas basis	6.72 to 26.98
Incinerators burning dry sewage sludge	3.17 to 4.35
Silica-rock treatment	
Oil-fired rotary dryer	6.42 to 23.50
Preheater gases	6.65 to 15.80
Ventilating system	9.37 to 26.20
Tin smelting	
Reverberatory furnaces	2.20 to 3.12
Calcining tin ores--rotary kilns	1.44 to 4.59
Zinc sintering machine--straight and chloridized roast	0.311 to 1.908
Zinc-ore roasting	
Flash roaster	3.92 to 45.05
Multiple-hearth roaster	3.82 to 7.07
Zinc oxide--Waelz plant	12.65 to 28.62

Table 47. AVERAGE DIAMETER OF PARTICLES IN VARIOUS INDUSTRIAL OPERATIONS TYPICAL OF ELECTRICAL PRECIPITATOR INSTALLATIONS (Kirk and Othmer, 1947)

Particle	Average diameter, μ
Coal dust	10
Powdered-coal ash	1 to 150
Tobacco smoke (tar mist)	0.25
Cement dust	5 to 100
Talc dust	10
Silica dust	5
Sprayed-zinc dust	15
Flour-mill dust	15
Alkali fume	1 to 5
Ammonium chloride fume	0.1 to 1
Zinc oxide fume	0.05
Condensed-zinc dust	2
Pigments	0.2 to 5
Sprayed dried milk	0.1 to 3

lecting troughs below. In the case of acid mist collectors, a continuous film of water is maintained on the tube wall by means of weirs. The tube-type precipitator is also commonly used in the steel industry to clean combustible gas from blast furnaces to prevent fouling of the gas burners.

Removal of dust from collecting electrodes

Once the dust or fume has been precipitated on the collecting electrode or plate, it must be removed to a hopper or storage depository. In order to do this, rappers are commonly employed. The plates are struck sharp, hammer-like blows to dislodge the collected dust, which then falls by gravity into the collecting hopper. Reentrainment of a portion of the dust at this point must be held to a minimum. Frequently, satisfactory collection efficiency is completely negated by improperly operated or adjusted rappers.

For fly ash precipitation, the dust buildup on the collecting plates should be allowed to reach about 1/4 to 1/2 inch before it is rapped off. Discharge electrode rappers are necessary when treating ashes predominantly composed of fine particles less than 10 microns in diameter (White, 1953).

A satisfactory rapping system is characterized by a high degree of reliability, by ability to maintain uniform and closely controlled raps over long periods of time without attention, and by flexible and easily controlled rapping intensity. The usual practice is to rap sufficiently to dislodge all the dust layer at one time. Stack puffs are prevented by rapping only a small fraction of the electrodes at a time and using proper sequence.

Rapping mechanisms include mechanical (electric motor operated) and pneumatic or air operated. Most new installations, however, now use magnetic solenoid-operated rappers, which can be adjusted more accurately to control both frequency and intensity of the raps.

Rapping is usually done in zones, the number and location of rappers being dictated by the size and configuration of the precipitator. Rappers are always adjusted in the field under operating conditions. Factors that influence the intensity, frequency, and number of blows required per cycle include:

1. Agglomerating characteristics of the dust,
2. the rate at which the dust is accumulated on the collecting electrode,
3. the tendency of the dust to become reentrained,
4. the effect of the accumulated dust on the electrical operation of the precipitator, and
5. the cycle of operation of the equipment being served.

In some cases where reentrainment is a severe problem, precipitators may be designed so that a number of sections may be closed in turn during rapping by means of dampers. While this may reduce the reentrainment loss during rapping, the usual practice is to rap during normal operation. When the equipment being served operates in cycles, it may be possible to bypass the precipitator for rapping during periods when little or no air contaminants are being vented. In some unusual cases it may be necessary to deenergize the precipitator in order to obtain effective removal of the collected dust during rapping. In other cases deenergizing may suffice to permit the collected dust to fall to the hopper by its own weight without the need to rap. With tube-type precipitators, when operated wet, it is not necessary to use rapping. Some plate-type precipitators are also operated without rappers for various reasons. For example, when transite plates are used, rapping is undesirable because these plates do not have adequate mechanical strength to withstand repeated blows. Hence, periodic water sprays are usually used in this case to wash the collected dust off the plates. Cycling the water sprays properly makes possible keeping the plates wet between flushings, which is a great aid in improv-

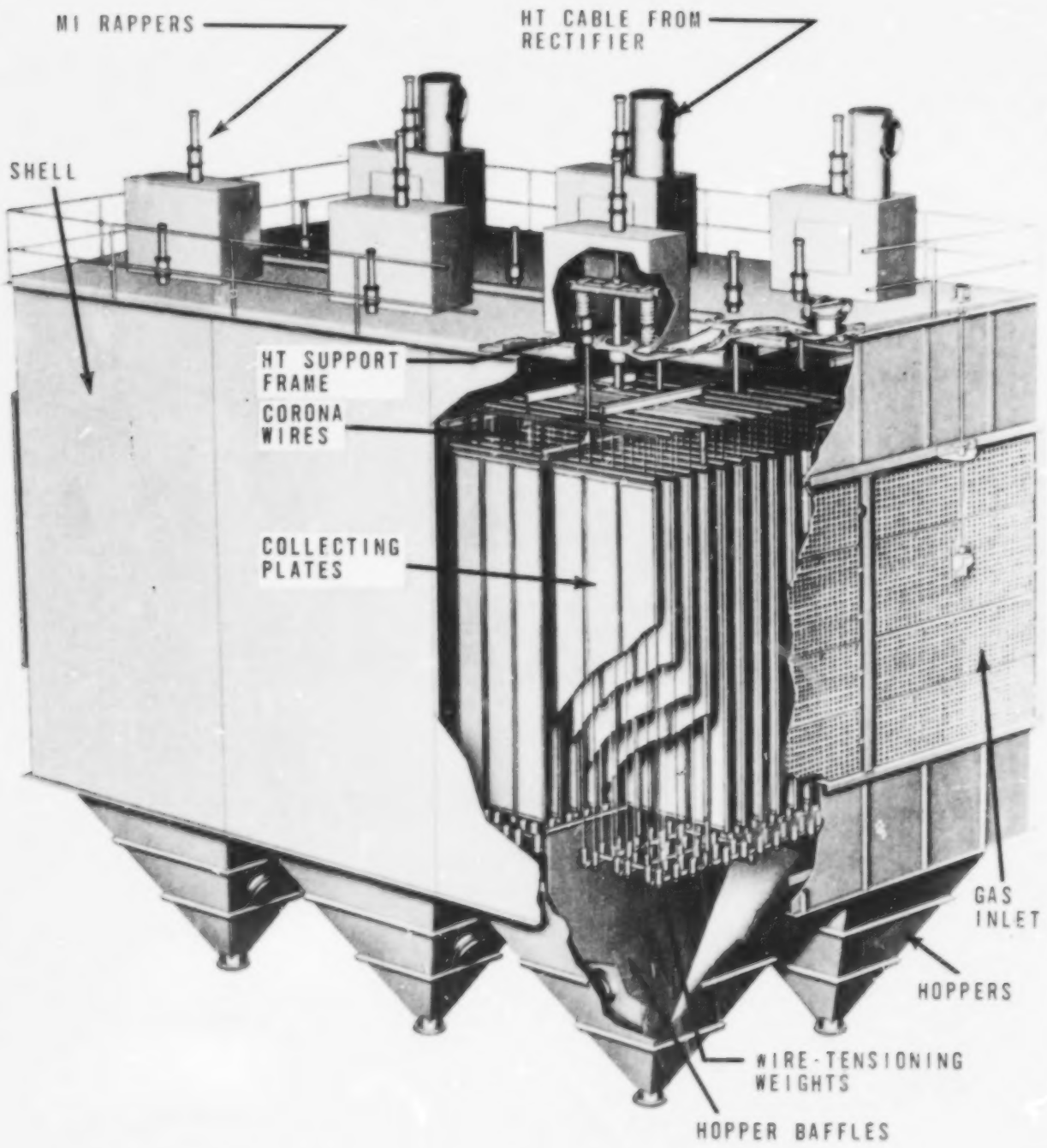


Figure 82. Basic structure of a typical precipitator (Western Precipitation, Division of Joy Manufacturing Co., Los Angeles, Calif.).

ing collection efficiency by minimizing reentrainment. The water sprays, when used, temporarily disrupt the electrical operation, so that this method is employed only in unusual cases.

Precipitator shells and hoppers

Precipitator shells may be made of a variety of materials. These include ordinary mild steel, lead-coated steel, acid-resisting brick and cement, poured concrete, carbon, tile, aluminum, wood, wrought iron, alloys of steel, rubber-coated steel, and vinyl, or other plastic coatings on steel or other supporting structures.

The collected dust is ordinarily stored in hoppers below the collecting electrodes for periodic or continuous disposal. Adequate storage must be provided to accommodate the collected dust between hopper cleanouts. If the dust

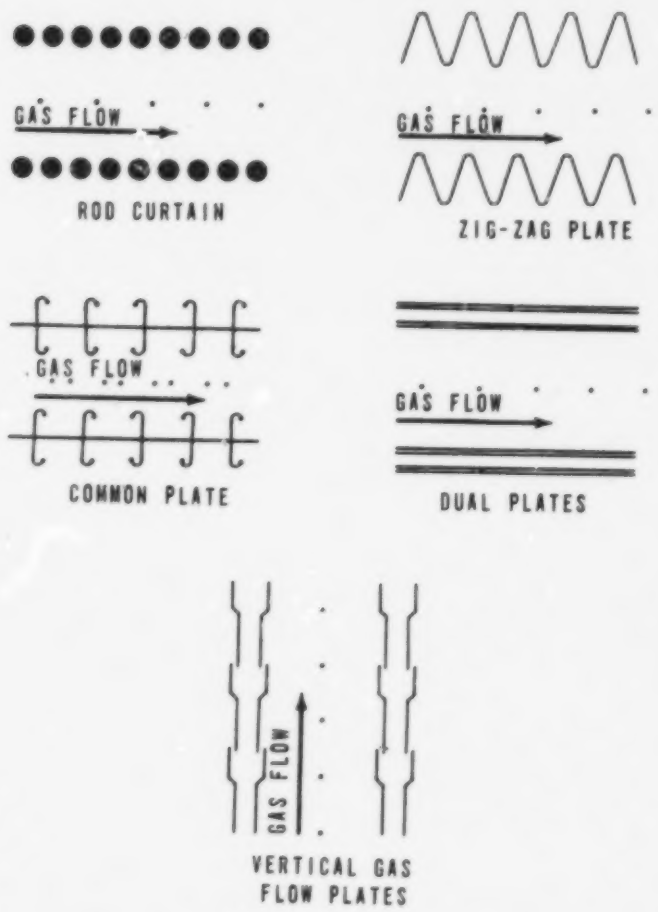


Figure 83. Some special collecting electrodes used in electrical precipitators (Western Precipitation, Division of Joy Manufacturing Co., Los Angeles, Calif.).

builds up to too high a level in the hopper, there is danger of reentrainment or shorting the discharge electrodes, or both. The sides of the hoppers must have adequate slope to prevent bridging and hangup. Vibrators may be required if the dust or fume does not move freely. Discharge from the hoppers may be by means of slide gates, motor-operated rotary valves, or screw conveyors. The latter two are suitable for continuous operation.

High Voltage for Successful Operation

In order to achieve maximum collection efficiency, electrical precipitators are operated as close to the sparking voltage as practicable without excessive sparking. The following gives the order of magnitude of current and field strength usually encountered in practice (Perry, 1950).

i_o = 3×10^3 to 3×10^4 statampere/cm (0.03 to 0.3 milliampere/ft)

E = 5 to 20 statvolt/cm (3.8 to 15.3 kilovolts/in.)

The values of the potential difference used in single-stage electrical precipitation are usually from 20,000 to 100,000 volts. Since unidirectional current is required for electrical precipitation, it is necessary to transform the available power to a high voltage and then rectify the high voltage. Early precipitators used mechanical rectification exclusively, and many of them are still in use.

Tube-type rectifiers

Electronic tube rectifiers were first used in electrical precipitation around 1920. The early tubes were unsatisfactory because of their short, uncertain life. These tubes have now been developed to the point where the average life in electrical precipitation service is in excess of 20,000 hours. In some cases over 30,000 hours of service have been obtained.

Filament voltage adjustment on tube rectifiers is a critical factor in tube life. As a rough guide, increasing filament voltage by 5 percent reduces filament life by a factor of 2 while reducing voltage by 5 percent increases filament life by a factor of 2. Thus, it is general practice to operate tube filaments in precipitator service at 5 to 10 percent below rated values, that is, at 18 to 19 volts rather than 20 volts, which is the rated value for most precipitation rectifier tubes (White, 1953).

Solid-state rectifiers

The development of solid-state rectifiers has made mechanical rectification obsolete. Selenium rectifiers provide reliable service with long life; however, they are subject to damage from excessively high temperatures. Silicon rectifiers, which are even newer in precipitation service, do not have the shortcoming of being subject to temperature damage. Although the solid-state rectifiers are somewhat more expensive than the electronic-tube type, their use is justified on the basis of a long, useful life and troublefree operation. Life expectancy of selenium rectifiers is estimated to be about 100,000 hours. Silicon rectifiers, which are hermetically sealed, appear to have unlimited life (Peach, 1959).

Effects of Wave Form

Rectifier connections are either half wave or full wave. The half wave connection is preferred in some cases, since it permits a greater degree of precipitator sectionalization with a given number of electrical sets. In

large precipitators, the corona electrodes are always subdivided into several groups or sections, and the individual sections separately energized by individual rectifier sets. This arrangement permits each section to be operated under optimum conditions and is necessary for optimum performance. Although half wave connection is sometimes preferred, full wave is usually used on the outlet sections, to supply the greater corona current demand required for these sections.

Typical operating voltages for fly ash precipitators of 8- or 9-inch plate-to-plate spacing range between 40 and 55 kilovolts. Corona currents usually lie between 10 and 30 milliamperes per 1,000 feet of discharge wire. The average electric power supplied to the corona commonly ranges between 40 and 120 watts per 1,000 cubic feet per minute of gas treated. In general, higher voltage and power provides higher precipitator efficiency and performance (White, 1953).

Controlled Sparking Rate

Recent research has shown that, contrary to earlier ideas, optimum collection efficiency is usually obtained with precipitator voltages set high enough to produce a substantial amount of sparking (White, 1963). Some precipitators, however, operate with practically no sparking. The optimum degree of sparking depends upon many factors, such as precipitator size, fume characteristics, fume concentration, and so forth. Maximum efficiency usually occurs from 50 to 100 sparks per minute. Figure 84 illustrates the variation of precipitator efficiency with sparking rate for a particular combination of precipitator design and operating conditions, such as temperature, moisture content, and so forth.

Figure 84. Variation of precipitator efficiency with sparking rate for a representative fly-ash precipitator (White, 1953).

Operating Voltage

The operating voltage of a precipitator cannot be predicted precisely. Dust conditions have an important bearing on the operating voltage. For practical purposes, each manufacturer standardizes on a limited number of basic transformer voltages. For example, one manufacturer (Cottrell Electrical Precipitators, 1952) designs all equipment around transformer ratings of 30,000; 60,000; 75,000; and 90,000 volts secondary.

The use of automatic voltage control results in increased collection efficiency from the same size precipitator or permits the use of a smaller precipitator for the same collection efficiency. The precipitator voltage is maintained at the optimum value by a spark counter or current-sensing feedback circuit. Once the control has been set for the desired spark rate, the precipitator is held constantly at maximum efficiency regardless of fluctuating conditions and without attention from an operator.

Uniform Gas Distribution

The average velocity of the gas in the duct upstream from a precipitator is usually 40 to 70 feet per second. In the treater, however, the gas velocity is 2 to 8 feet per second. Because maintaining uniform gas velocity and dust distribution in the treater is important, much attention has been paid to the transition from a high velocity in the duct to a low velocity in the precipitator. Splitters are almost universally used in all bends or elbows in the approach to the precipitator. This also helps reduce the draft loss. Distribution grids of many types have been developed, some of which are shown in Figure 85. The choice of type to use in a particular installation can usually be made reliably only by means of scale-model studies. Much of the work in this field is trial and error until a reasonably uniform gas velocity distribution is obtained in the model. The percentage of open area has an important bearing on the performance of distribution grids. Experience may reduce the problem to one of degree rather than of kind so that all that need be determined is the optimum position of the grid. In some cases, installing a perforated plate at the outlet of the precipitator has been found as important as installing one at the inlet. A very common type of design consists of one or two flat perforated plates at the inlet of the treater.

Cost of Electrical Precipitator Installations

Table 45 shows the variation of costs for electrical precipitators depending upon the size, type of dust or fume, and efficiency required. Preliminary engineering studies and model studies for gas distribution may add substan-

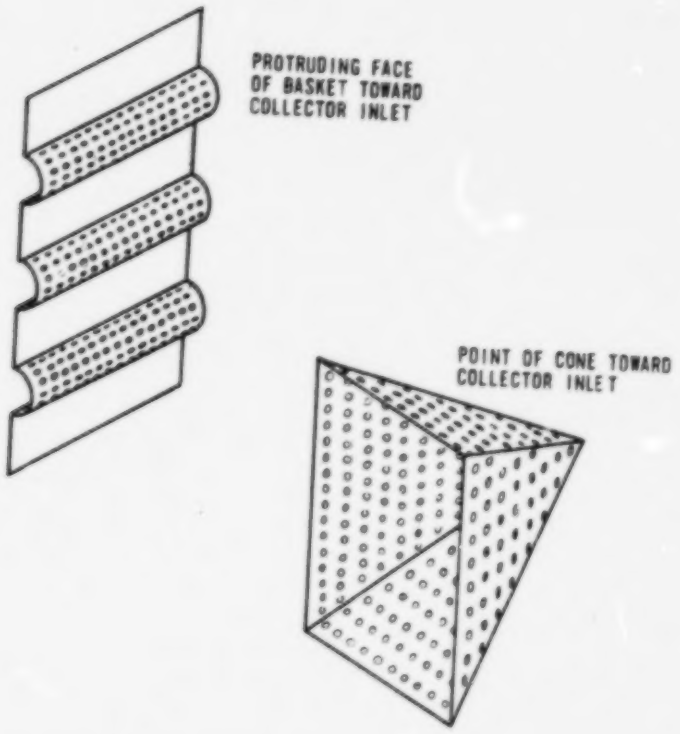


Figure 85. Examples of special perforated plate gas distribution grids (Western Precipitation Corporation, Division of Joy Manufacturing Co., Los Angeles, Calif.).

tially to costs shown. The costs of ductwork to and from the precipitator, of foundations, and of extending utility services to the area of the precipitator are in addition to the installed cost of the precipitator itself. Factors affecting the cost of the precipitator include the power supply (rectifier, automatic voltage control, number of sections individually energized, and so forth), special plate design, electrical characteristics of the dust or fume, collection efficiency required, and special materials or type of construction needed to resist corrosion or wear.

Theoretical Analysis of Precipitator Performance

A theoretical analysis of precipitator mechanisms and performance involves two fundamental processes, particle charging and particle migration. Many factors affect both these mechanisms.

Particle charging

In order to derive an expression for the rate of particle charging (White, 1951) and the maximum charge attained by a particle, the following assumptions are made:

1. The particles are spherical.
2. Particle spacing is much larger than particle diameter.
3. The ion concentration and electric field in the region of a particle are uniform.

These assumptions are reasonable approximations except for a few cases where the shape of the particle may depart radically from the spherical.

A particle entering the charging field of an electrical precipitator is bombarded by ions. Some strike the particle and impart their charge to it. As soon as a charge has been acquired by the particle, an electric field is created that repels similarly charged ions. Some ions continue to strike the particle, but the rate at which they do so continually diminishes until the charge acquired by the particle is sufficient to prevent further ions' striking it. This, then, is the limiting charge that can be acquired by the particle.

The motion of gas ions in the electrostatic field of an electrical precipitator constitutes an electric current

$$i = jA \tag{55}$$

where

i = electrical current, statampere

j = current density, statampere/cm^2

A = area, cm^2.

The ion current density in the undistorted field region outside the immediate influence of the particle is

$$j = N \varepsilon M E \tag{56}$$

where

N = number of ions per cm^3

ε = elementary electrical charge = 4.80 x 10^{-10} statcoulomb

M = ion mobility, $\frac{\text{cm/sec}}{\text{statvolt/cm}}$

The area of the ion stream that enters the particle is determined by the total electric flux as follows

$$A = \frac{\psi}{k E} \tag{57}$$

where

ψ = total electric flue. statcoulombs

k = permittivity of free space, numerically equal to 1 in the cgs electrostatic system of units.

From electrostatic principles the electric flux is found to be

$$\phi = \int_0^{\Theta} \left(p E \cos\Theta - \frac{n\varepsilon}{a^2} \right) 2\pi a^2 \sin\Theta \, d\Theta$$

$$= p\pi a^2 E \left(1 - \frac{n\varepsilon}{pEa^2} \right)^2 \qquad (58)$$

where

p = a factor defined in equation 61

n = number of elementary electrical charges acquired by a particle

a = radius of a particle, cm.

Substituting and noting that the ion current is determined by the number of elementary electronic charges in a given time

$$i = \frac{d(n\varepsilon)}{dt} = p\pi a^2 N \varepsilon M E \left(1 - \frac{n\varepsilon}{pEa^2} \right)^2 \qquad (59)$$

Upon integration, the number of elementary electronic charges acquired by a particle of radius a in time t is found to be

$$n = \frac{pEa^2}{\varepsilon} \cdot \frac{t}{t + \frac{1}{\pi N \varepsilon M}} \qquad (60)$$

where

p = a factor that depends upon the dielectric constant D of the particle. The numerical value of p ranges from a value of 1 for materials with a dielectric constant of 1 to 3 for some dielectric materials, and is defined by

$$p = 1 + \frac{2(D-1)}{(D+2)} \qquad (61)$$

As the time t becomes large the value of the limiting or saturation charge is

$$q_s = n_s \varepsilon = pEa^2 \qquad (62)$$

where

q_s = the limiting charge acquired by a particle, statcoulomb

n_s = the limiting number of elementary electrical charges acquired by a particle at saturation

E = strength of charging field at the point where the particle acquired its charge, statvolt/cm.

For conditions normally existing in average precipitators, charging can be considered reasonably complete in about 0.1 second. Since the gas velocities are usually 2 to 8 fps, a particle may travel only a few inches, or a foot at most, before it has for all practical purposes attained its limiting or saturation charge. Some charging also occurs by means of ion diffusion but this can usually be neglected for particles larger than about 0.5 micron in diameter and does not become a significant factor unless the particles are smaller than about 0.2 micron in diameter. The usual practice is to assume that only ion bombardment charging occurs. Any error introduced by this simplification is usually of less magnitude than the effects of nonuniform gas distribution, reentrainment, high dust resistivity, rapping losses, and other practical problems that usually increase the actual losses by a factor 2 or 3 times (White, 1953) the theoretical value. The particle-charging time constant t_o is defined as

$$t_o = \frac{1}{\pi N \varepsilon M} \qquad (63)$$

and is the time required for 50 percent of the limiting charge to be attained.

Particle migration

The force F_1 (in dynes) exerted on a charged particle in an electric field is proportional to the charge q (in statcoulombs) on the particle and the strength E_p of the electric field.

$$F_1 = q E_p \qquad (64)$$

where

E_p = strength of precipitating field, statvolt/cm.

This force accelerates the particle until the viscous drag, or resistance of the gas in which the particle is suspended, exactly equals the force exerted by the electric field. Under conditions normally existing in an electrical precipitator, the viscous drag F_2 (in dynes) is defined by Stokes' law

$$F_2 = 6\pi a u w \qquad (65)$$

where

a = radius of particle, cm

u = viscosity of gas stream, poise

w = velocity of a particle relative to the gas in which it is suspended, cm/sec.

Substituting the charge q acquired by the particle

$$F_1 = p E E_p a^2 \qquad (66)$$

Since F_1 must be equal to F_2 under equilibrium conditions, the equations may be equated. Solving for the particle velocity

$$w = \frac{p E E_p a}{6 \pi u} \qquad (67)$$

For most common materials the dielectric constant D is 2 to 8. Thus, the value of p varies from 1.50 to 2.40, or the average is very nearly 2. The charging field E and the precipitating field E_p are created by the same mechanism. Tests have shown that the field strength is not uniform, being highest in the vicinity of the discharge electrode (White and Penny, 1961). It is a common practice, however, in calculating the drift velocity, to assume that these are approximately equal. Making this assumption, and converting the cgs units to those more convenient for practical application, we obtain for a particle in air at 60°F

$$w = 8.42 \times 10^{-3} E^2 d p \qquad (68)$$

where

w = the particle drift velocity, ft/sec

E = the potential applied to the discharge electrodes, KV/in.

d = the diameter of the particle, microns

p = a factor as before.

If the medium is a gas other than air or if the air temperature departs from standard by more than about 50°F, a multiplying factor of 0.0178/u must be used to correct for the effect of viscosity, with u in centipoises.

In tests performed by White (1953) on an electrical precipitator collecting fly ash from an electric steam power plant, the drift velocity was calculated on the basis of actual measured efficiency. The drift velocity was found to be consistently about one-half that calculated from the theoretical equations. The theoretical equations, however, neglect such effects as nonuniform gas velocity, erosion of dust, rapping losses, corona quenching, high resistivity, half-wave rectification, and so on.

Theoretical Efficiency

The trajectory of a particle in an electrical precipitator can be determined if the following assumptions are made:

1. The strength of the precipitating field is uniform. This is nearly true except in the vicinity of the discharge electrode.

2. The migration or drift velocity w of the particle is constant. This is true for a particle with a constant charge in a uniform field. Since the limiting charge is closely approached within the first foot or less of travel, this is a valid approximation for the conditions actually encountered in precipitators.

3. The average forward velocity v of the particles suspended in the gas stream is uniform. Since precipitators almost always operate with Reynolds numbers in the turbulent range, the statistical mean velocity of the particles may be considered uniform in the direction of flow through the precipitator.

From the assumptions equation 69 is derived:

$$\frac{dv}{dt} = C_1 \frac{dw}{dt} = O \qquad (69)$$

where

v = mean velocity of a particle in the gas stream in the direction of gas flow, ft/sec

w = mean velocity of a particle perpendicular to the gas stream or in the direction of collecting electrodes, ft/sec.

By integration

$$v = C_1 w + C_2 \qquad (70)$$

The constants C_1 and C_2 depend upon dimensions of the precipitator, the field strength, the point at which the particle enters the electrical field,

the mean velocity of the particle through the precipitator, and the electrical properties of the particle and the particle diameter. Thus, the trajectory is different for each particle, but it is approximately a straight line. If all the particles have the same electrical characteristics, and the worst case of a particle's entering midway between the collecting electrodes is considered, the only variable is the particle diameter. For each particle diameter there is some finite length of collecting electrode required in order to achieve theoretical 100 percent collection efficiency. This length is defined by

$$L = \frac{sv}{w} \qquad (71)$$

where

L = length of collecting electrode in direction of gas flow, ft

s = separation of discharge and collecting electrodes, ft.

The calculation of the theoretical length required for 100 percent collection efficiency is illustrated by the following example:

Example 19

Given:

A plate-type precipitator with 8-in. plate-to-plate spacing and an applied voltage of 40,000 volts. Mean gas velocity through the precipitator is 5 fps and the minimum particle diameter is 0.5 μ.

Problem:

Find the minimum length of collecting electrode in the direction of gas flow required for 100% collection efficiency.

Solution:

1. Migration velocity from equation 68 using p = 1

$$w = (8.42 \times 10^{-3}) \frac{40^2}{4} (0.5) = 0.421 \text{ fps}$$

2. Length of collecting electrode from equation 71

$$L = \frac{(0.333)(5)}{(0.421)} = 4.0 \text{ ft}$$

If charging is considered practically complete in 0.2 sec, an additional 1 ft must be added to allow for the distance traveled by the particle while being charged. The length of collecting electrode in the direction of gas flow required for 100% collection efficiency is therefore 5 ft theoretically.

Deficiencies in Theoretical Approach to Precipitator Efficiency

Example 19 illustrates that 100 percent collection efficiency should result theoretically from a precipitator 5 feet long in the direction of gas flow when the particles suspended in the gas are 0.5 micron or larger. This particle size is fairly typical of that encountered in practice. The length of a precipitator is, however, generally between 8 and 24 feet in the direction of gas flow. Yet no precipitator operates with 100 percent collection efficiency and, in fact, very few operate with collection efficiencies much greater than 98 percent. The precipitator in Example 19, if only 5 feet long, might possibly fail to exceed 50 percent collection efficiency in an actual case, depending upon the electrical properties of the particles, operation of the rappers, and other factors not considered in the theoretical approach.

Effects of Resistivity

A dust such as carbon with very low electrical resistivity (Schmidt et al., 1950) readily relinquishes its negative charge to the collecting electrode and assumes a positive charge. Since positive charges repel each other, the carbon particle is repelled from the collecting electrode into the gas stream where it is bombarded by negative ions and becomes negatively charged again. The particles are thus alternately attracted and repelled and so skip through the precipitator, knocking other particles, which have already been collected, off the collecting electrode.

If the dust, for example powdered sulfur, has a high electrical resistivity, it is unable to give up its negative charge to the collecting electrode. As the layer of dust builds up on the electrode, it acts as an insulator. The potential drop across this dust layer may build up to high values, which may have an adverse effect on the corona discharge and may set up a secondary brush discharge at and within the dust layer. This condition is called "back discharge" or "back corona," and may seriously impair the performance of the precipitator.

When the dust, for example cement dust, has medium resistivity, it can relinquish part of

its charge to the collecting electrode. The rate at which the charge leaks off increases as the dust layer builds up and the potential drop across the dust layer increases until a condition of equilibrium is achieved. Sufficient negative charge is retained by the particles to maintain a force of attraction between the particles and the collecting electrode. When the weight of the collected dust becomes sufficiently great, particles fall off, of their own weight, or are jarred loose when the electrodes are rapped.

The electrical resistivity varies with temperature and moisture, as illustrated in Figure 86 for some representative dusts. Collection efficiency is adversely affected when the electrical resistivity is as low as 10^4 ohm-centimeter or as high as 10^{10} ohm-centimeter. Apparently then, for many materials, collection efficiency is adversely affected when the temperature is 250 to 400°F, the range in which it is normally desired to operate the precipitator. The adverse effects of high resistivity may be avoided by operating at a higher temperature, but this is usually not desirable because of the additional heat losses. Operation at lower temperatures to the left of the peak of the resistivity curve is frequently objectionable because of excessive corrosion. An alternative is to increase the moisture content or add other conditioning agents.

The addition of water vapor, acid, or other conducting material increases the surface conductivity of high-resistivity dusts by adsorption on the particle surfaces, which reduces the apparent electrical resistivity. Some materials used as conditioning agents include water vapor, ammonia, salt, acid, oil, sulfur dioxide, and triethylamine (Schmidt and Flodin, 1952).

In addition to the beneficial effects on the electrical resistivity of the dust by the addition of moisture, water vapor has a pronounced effect on the sparking voltage in an electrical precipitator. This effect is shown graphically in Figure 87, plotted from experimental data. In most cases the effect of the moisture on the electrical resistivity of the dust predominates when the temperature is below 500°F, and the effect of the moisture in increasing the sparking potential predominates at temperatures above 500°F (Sproull and Nakada, 1951).

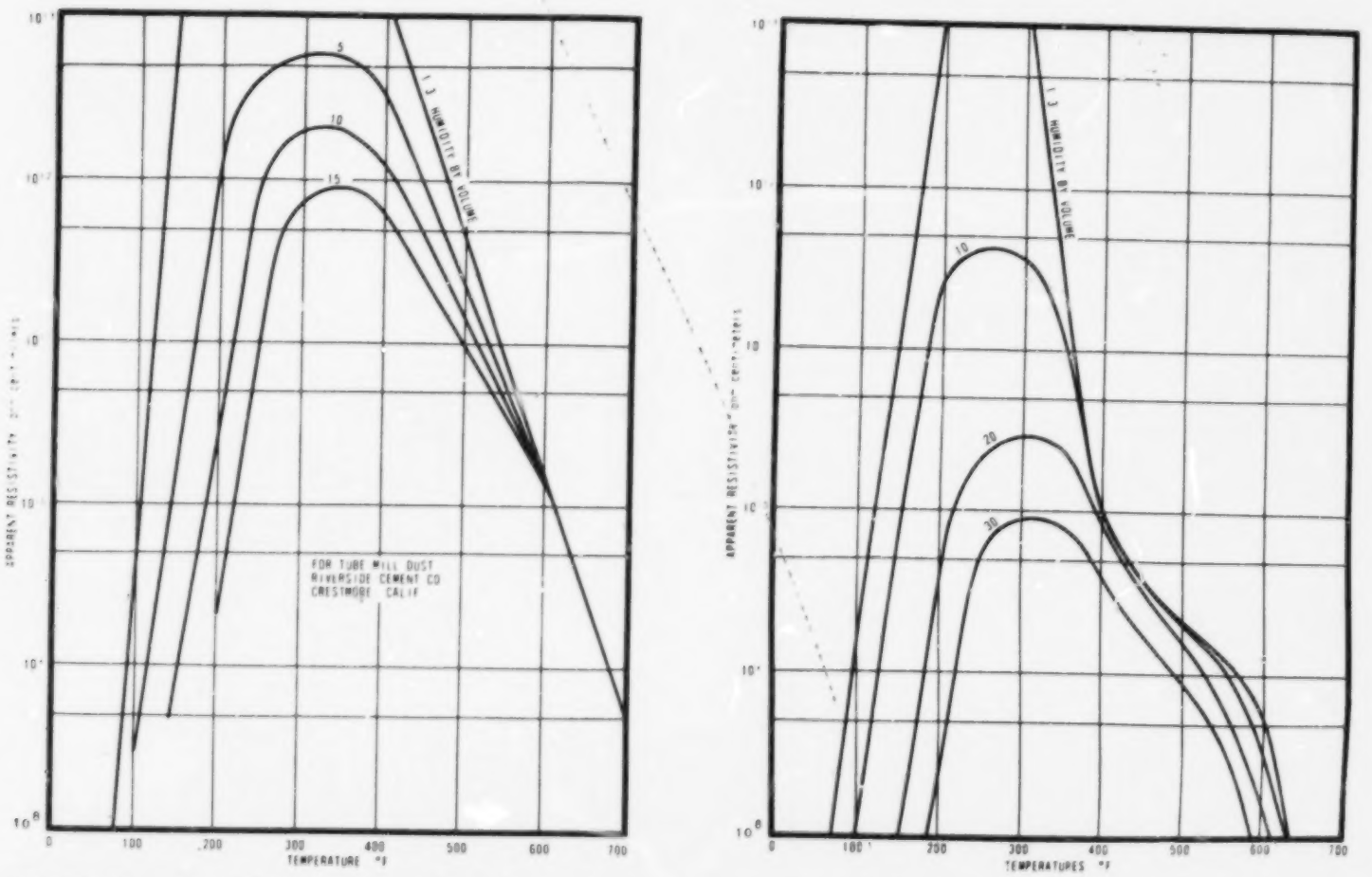


Figure 86. Variation of apparent resistivity with temperature and moisture for some typical dusts and fumes; (left) apparent resistivity of powdered lime rock used in making Portland cement; (right) apparent resistivity of fume from open-hearth furnace (Sproull and Nakada, 1951).

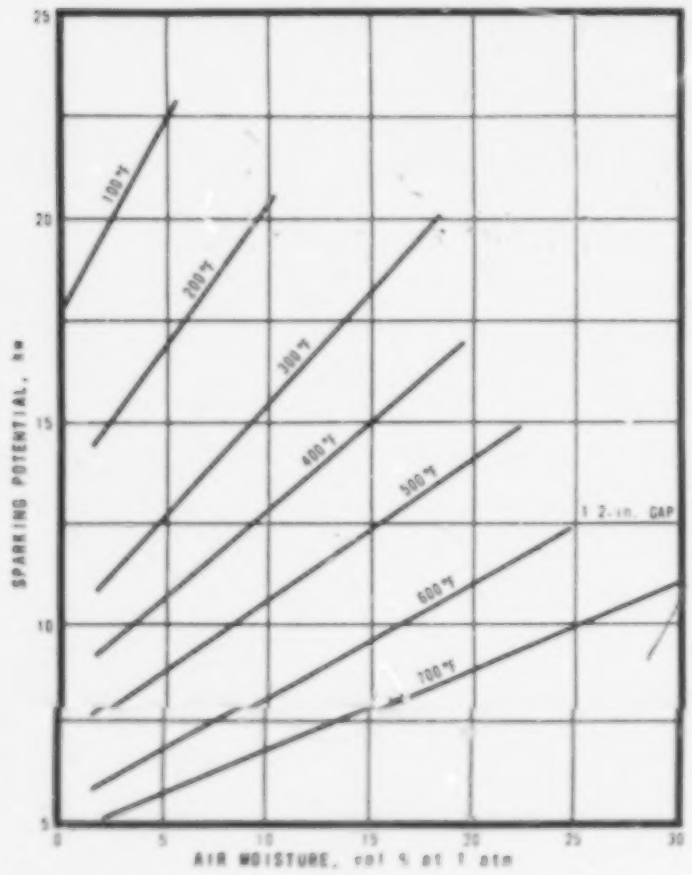


Figure 87. Sparking potential for negative point-to-plane 0.5-inch gap as a function of the moisture content of air at 1 atmosphere pressure for various temperatures (Sproull and Nakada, 1951).

Although there is no doubt that the electrical properties of dusts and fumes may drastically affect the operation of a precipitator, knowledge of quantitative relationships in this respect is limited. It is known that performance is reduced as the electrical resistivity becomes exceptionally large or small. Some data have been published on the variation of electrical resistivity with temperature and humidity for a few dusts and fumes. Sproull and Nakada (1951) analyze the potential drop across a layer of collected dust. Precipitation theory has not yet been developed to the point where collection efficiency can be accurately predicted without reliance on empirical data.

Methods of Reducing Reentrainment

Unless the dust collected by the precipitator can be retained, the entire effort is wasted. Once it is collected by the collecting electrode, the dust may be reentrained into the gas stream owing to (1) low resistivity, which permits the negative charge to leak off too rapidly and a positive charge to be acquired; (2) rapping; and (3) erosion of the collected dust from the collecting electrode. This may be because of nonuniform gas velocity, which results in excessively high velocity through some sections of the precipitator or excessive turbulence.

The effects of low resistivity are not amenable to correction. Fortunately, this problem does not frequently arise. In the case of carbon black, which has too low a resistivity to permit precipitation, a practical solution has been found. The electrical precipitator agglomerates the particles of carbon that cannot be retained on the collecting electrodes because of their low resistivity. The agglomerated particles are collected by a centrifugal collector that follows the precipitator.

To reduce erosion of dust from the collecting electrodes, various special designs of electrodes are used. The objective in all these designs is to provide quiescent zones to prevent or reduce erosion. The difficulty is reduced materially by good gas distribution in the precipitator. The original design must take into consideration the nature of the dust so that the maximum velocity through the treater will be less than the critical value at which erosion begins to increase sharply. The critical velocity for any particular dust can be determined only by actual test. Some typical values for the gas velocity at which erosion becomes significant are 2 fps for carbon black, 8 fps for fly ash and 10 to 12 fps for cement kiln dust (Schmidt, 1949).

Dust reentrainment during rapping is controlled by adjusting the rapping cycle and intensity to minimize the degree of reentrainment. Rapping cycles are determined experimentally after the precipitator is placed in normal operation.

Rose and Wood (1956) analyze the theoretical collection efficiency when reentrainment is considered to show that the equation for the loss takes the form

$$\text{Loss} = C\, e^{kt} \qquad (72)$$

where

C and k = constants that depend upon the configuration of the precipitator, properties of the dust, and many other variables

e = the base for Naperian logarithms = 2.71828

t = the time a dust particle remains in the precipitating field of the precipitator, sec.

Present knowledge of precipitation theory does not permit an accurate evaluation of the constants C and k. Their values must be determined empirically.

Practical Equations for Precipitator Design and Efficiency

Empirical equations have been developed by Anderson (1924), Walker and Coolidge (1953), Schmidt (1928), Deutsch (1922), and others.

Deutsch published a proposed equation with a form similar to

$$\eta = 1 - e^{-wf} \qquad (73)$$

where

η = weight fraction of dust collected

w = velocity of drift or migration of a dust particle toward the collecting electrode, fps

f = ratio of area of collecting electrodes to the volume of gas passing through the treater, ($ft^2/ft^3/sec$).

Anderson proposed an equation of the form

$$\eta = 1 - K^t \qquad (74)$$

where

K = an empirical constant

t = the time a dust particle remains in the electrical field of the treater, sec.

Schmidt modified the Anderson equation to

$$\eta = 1 - K^{\frac{cA_p}{Q}} \qquad (75)$$

where

K and c = empirical constants

A_p = the area of the collecting electrodes or plates, ft2

Q = the gas volume, cfs.

Frequently the following modified forms are used:

Plate-type precipitators

$$\eta = 1 - K^{Ct} \qquad (76)$$

tube-type precipitators

$$\eta = 1 - K^{2Ct} \qquad (77).$$

K is a measure of the ease with which the dust or fume can be precipitated, and C depends upon the physical dimensions of the precipitator and the voltage applied. For any particular installation both K and C must be considered constants since otherwise the equations are not useful. It is easy to show that the last three equations are equivalent.

For plate-type precipitators

$$\eta = 1 - K^{Ct}$$

$$C = \frac{c}{s}$$

$$t = \frac{L}{V}$$

$$\eta = 1 - K^{\frac{cL}{sv}}$$

$$v = \frac{Q}{W\,2s}$$

$$A = 2\,L\,W$$

$$\eta = 1 - K^{\frac{cA_p}{Q}}$$

where

c = a constant

s = separation or distance between discharge electrode and collecting electrode, ft

L = length of collecting electrode in the direction of gas flow, ft

v = mean velocity of gas in the direction of flow through the treater, fps

W = width of collecting electrode or dimension perpendicular to direction of gas flow, ft

A = area, ft^2

A_p = area of collecting electrode or plate, ft^2.

For tube-type precipitators

$$\eta = 1 - K^{\frac{2cL}{sv}}$$

$$v = \frac{Q}{\pi s^2}$$

$$A = 2\pi s L$$

$$\eta = 1 - K^{\frac{cA_p}{Q}}$$

Figure 88 graphically illustrates the relationship among several common forms of these efficiency equations. Note that in each equation there is at least one arbitrary constant whose value determines the efficiency. This is referred to as the precipitation constant in the Anderson and Schmidt equations and the drift velocity in the Deutsch equation. In reality, this is neither a constant nor a true representation of the drift velocity. Some typical values of the so-called drift or migration velocity are listed in Table 48.

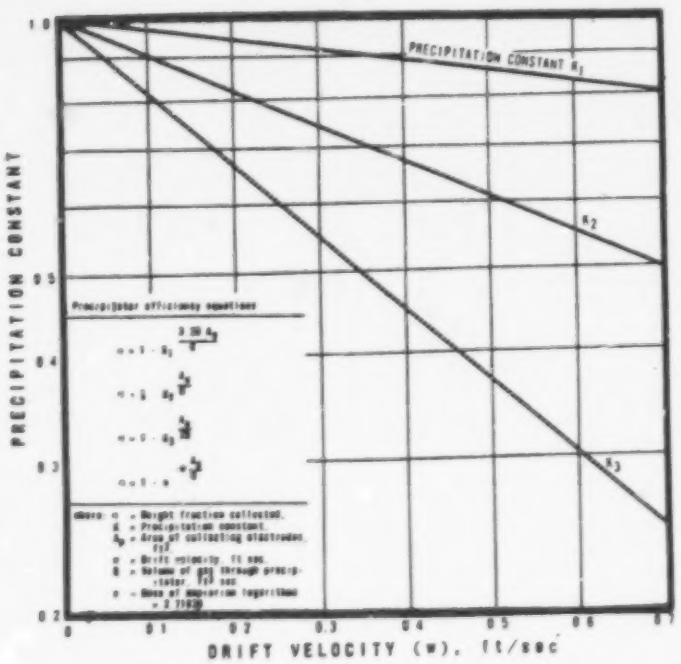


Figure 88. Relationship among various precipitation constants and drift velocity.

Table 48. TYPICAL VALUES OF DRIFT VELOCITY ENCOUNTERED IN PRACTICE FOR USE WITH EFFICIENCY EQUATION

$$\eta = 1 - e^{-w\frac{A_p}{Q}}$$

Application	Drift velocity (w), ft/sec
Pulverized coal (fly ash)	0.33 to 0.44
Paper mills	0.25
Open-hearth furnace	0.19
Secondary blast furnace (80% foundry iron)	0.41
Gypsum	0.52 to 0.64
Hot phosphorous	0.09
Acid mist (H_2SO_4)	0.19 to 0.25
Acid mist (TiO_2)	0.19 to 0.25
Flash roaster	0.25
Multiple-hearth roaster	0.26
Portland cement manufacturing (wet process)	0.33 to 0.37
Portland cement manufacturing (dry process)	0.19 to 0.23
Catalyst dust	0.25
Gray iron cupola (iron-coke ratio = 10)	0.10 to 0.12

The drift velocity w and precipitation constant K are usually variables that are affected by the electrical properties of the particles, which in turn, vary with temperature and humidity, and by the applied voltage and the ionic current, which depend upon the temperature, humidity, and dust load. They must also reflect the effects of reentrainment and rapping losses, as well as nonuniform gas velocity distribution. In general, the effects of none of these factors can be predicted analytically with any degree of accuracy.

The design of electrical precipitators is today almost entirely empirical. Designs are based either upon previous experience with similar processes or upon the results of pilot model precipitator studies. Table 49 shows average values for the major variables in precipitator design. Precipitator manufacturers have accumulated considerable data through the years upon which they can base the design of new installations.

Effects of Nonuniform Gas Velocity

The importance of uniform gas velocity through the treater cannot be overemphasized. In all precipitator efficiency equations an increase in the gas velocity or flow rate reduces the efficiency exponentially. Conversely, a decrease

Table 49. TYPICAL VALUES OF SOME DESIGN VARIABLES USED IN COMMERCIAL ELECTRICAL PRECIPITATOR PRACTICE

Design variable	Normal range of values
Plate spacing	8 to 11 in.
Velocity through precipitator	2 to 8 ft/sec
Vertical height of plates	12 to 24 ft
Horizontal length of plates	0.5 to 1.0 x height
Applied voltage	30 to 75 kv
Drift velocity w	0.1 to 0.7 ft/sec
Gas temperature	up to 700°F standard 1,000°F high temperature 1,300°F special
Treatment time	2 to 10 sec
Draft loss	0.1 to 0.5 in. WC
Efficiency	up to 99.9+% usually 90% to 98%
Corona current	0.01 to 1.0 ma/ft wire
Field strength	7 to 15 kv/in.

in gas velocity or flow rate increases the efficiency exponentially. For a constant volume of gas through the precipitator, maximum efficiency is attained when the velocity is uniform. As the velocity increases through one section of the precipitator, collection efficiency decreases. At the same time the velocity must decrease through other parts of the precipitator since the total flow rate remains the same. The efficiency for the sections having the lower velocity will increase. The increase in efficiency through the low-velocity sections of the precipitator can never compensate for the loss in efficiency through the high-velocity portions of the precipitator. This is illustrated by example 20:

Example 20

Given:

A horizontal-flow, single-stage electrical precipitator consisting of two ducts formed by plates 8 ft wide x 12 ft high on 10 in. centers, handling 3,600 cfm with two grains of dust/ft^3. The drift velocity is 0.38 fps.

Problem:

Find collection efficiency and dust loss in lb/hr for (1) Uniform gas velocity and (2) peak velocity 50% greater than average.

Solution:

For either case the loss is given by

$$\text{Loss} = \frac{(1-\eta)(60)(60)(Q)(G)}{(7,000)} \text{ lb/hr}$$

where G = dust concentration, grains/ft^3.

For uniform gas velocity, collection efficiency is given by

$$\eta = 1 - e^{-w\frac{A_p}{Q}}$$

The plate area of each duct is

$$A = (2)(8)(12) = 192 \text{ ft}^2$$

The flow rate per duct is

$$Q = \frac{(3600)}{(2)(60)} = 30 \text{ ft}^3/\text{sec}$$

For uniform gas velocity

$$\eta = 1 - e^{-0.38\frac{192}{30}} = 0.912 \text{ or } 91.2\%$$

$$\text{Loss} = \frac{(1-0.912)(3600)(60)(2)}{(7,000)} = 5.42 \text{ lb/hr}$$

For simplicity, assume that the velocity through one of the ducts is 50% greater than average or the volume is 2,700 cfm and the volume through the other duct is 50% less than average or 900 cfm. In an actual case where the velocity varies continuously, it would be necessary to divide the precipitator into a great number of zones, each having approximately constant velocity. The procedure is illustrated by this simplified approach.

For the high-velocity duct

$$\eta = 1 - e^{-0.38\frac{192}{45}} = 0.8025 \text{ or } 80.25\%$$

$$\text{Loss} = \frac{(1-0.8025)(2,700)(60)(2)}{(7,000)} = 9.15 \text{ lb/hr}$$

For the low-velocity duct

$$\eta = 1 - e^{-0.38\frac{192}{15}} = 0.9922 \text{ or } 99.22\%$$

$$\text{Loss} = \frac{(1-0.9922)(900)(60)(2)}{(7,000)} = 0.12 \text{ lb/hr}$$

The total loss for the two ducts with nonuniform velocity is 9.15 + 0.12 = 9.27 lb/hr. This is 71% greater than the 5.42 lb/hr loss with uniform gas velocity.

Figure 89 gives multiplying factors to correct the loss for the effects of nonuniform gas velocity. This graph was prepared by means of

calculations similar to those in example 20. In an actual case, since less than 50 percent of the precipitator would be subjected to peak gas velocities, the adverse effects of nonuniform gas distribution would be less severe. On the other hand, in an actual precipitator, reentrainment would be aggravated in the higher velocity sections so that the actual losses in an extreme case could be several times that predicted solely on the basis of velocity distribution.

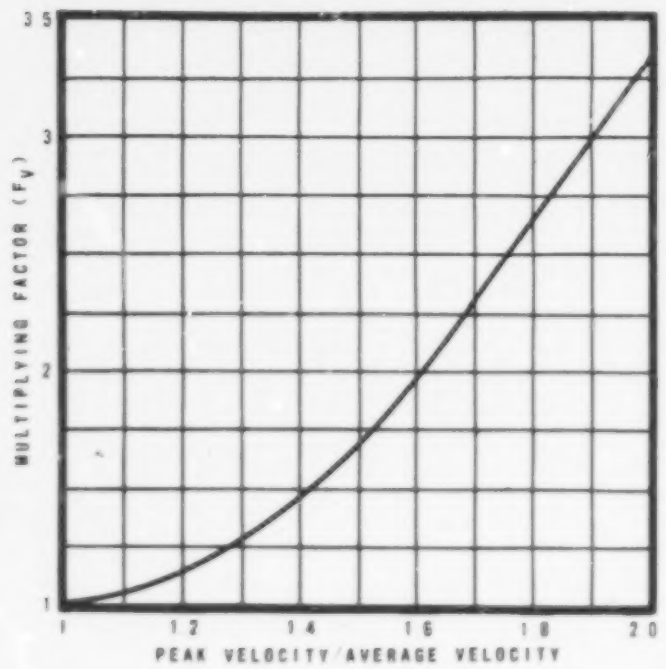


Figure 89. Multiplying factors for loss from electrical precipitator with nonuniform gas distribution. Loss equals $F_v L_0$, where L_0 equals loss with uniform gas distribution.

Important Factors in the Design of a Precipitator

The following design factors are critical elements in an electrical precipitator (Schmidt and Flodin, 1952): (1) Proportion, (2) capacity, (3) cleaning of electrodes, (4) reliability of components, (5) stability of electrical system, (6) accessibility for maintenance, (7) control of gas flow, (8) control of erosion of dust from electrodes, and (9) power supply. This list is not intended to be exhaustive or in order of importance. All these items are interrelated, and optimum performance cannot be achieved if there are shortcomings in any of them. The designer of an electrical precipitator is faced with many decisions for which there is no clear-cut solution.

Oftentimes, the most important factor in determining the length and width of a precipitator is the available space. This factor also introduces problems in the design of the ductwork leading to and from the precipitator. Thus, it may be necessary to increase the height of a horizontal-flow precipitator because of a space limitation on the length. Since the time in the treater is reduced by restricting the length, an additional increment of height is required to compensate. Because this increases the difficulty of providing uniform gas distribution, an additional increment of height is required to compensate for nonuniform gas velocity distribution. The increased plate height introduces additional problems in maintaining uniform plate-to-plate distance and in the discharge electrode's suspension system. Optimum performance requires uniform field strength through all sections of the precipitator, which in turn, depends upon near perfect alignment of the electrode system. Even a small variation in spacing of discharge electrode to collecting electrode can seriously reduce the performance. Greater plate height may also increase the dynamic instability of the discharge electrode system, that is, it may increase the tendency of the discharge electrodes to swing or vibrate.

The tendency of the discharge electrodes to swing or vibrate is overcome to some extent by guides and heavy weights attached to the lower end of the wires. Some sparking is desirable in a precipitator, but with less than perfect alignment, the sparking will occur most frequently only at points where the wire-to-plate spacing is the least, usually at the lower edge of the plate. The difficulty is frequently reduced or overcome by using shrouds on the lower edge of the plate or on this section of the discharge electrode.

SUMMARY AND CONCLUSIONS

Electrical precipitation is suitable for the collection of a wide range of dusts and fumes. In some cases, for example detarring, it is the only feasible method; in other cases, it may be the most economical choice. The design of an electrical precipitator requires considerable experience for successful application. The fundamental theory of the mechanisms involved in electrical precipitation is only partially understood at present. Further research will tend to make the design of electrical precipitators more of a science and less of an art.

TWO-STAGE ELECTRICAL PRECIPITATORS

The Cottrell-type precipitator is usually designed and custom built specifically for installations required to process large volumes of

contaminated air. Since 1937 a somewhat different type has been marketed. This unit, developed by Penney (1937), is now called the low-voltage, Penney, or more commonly, the two-stage precipitator. It is also occasionally referred to as the air-conditioning precipitator or "electronic air filter" (White, 1957).

The two-stage unit differs from the Cottrell type in that the contaminated air is first passed through a variable-strength ionizing field before being subjected to a separate uniform field where the charged particles are collected. Figure 90 shows the fundamental arrangement of the active electrical components. Basic operating principles are the same as those discussed for the Cottrell precipitator. A high-voltage corona discharge ionizes gas molecules that cause charging of particles passing through the field. The charged particles then tend to migrate toward electrically grounded or oppositely charged surfaces where they are removed from the airstream.

Most of the early applications of the two-stage precipitators were for removal of tobacco smoke, pollen, and similar air contaminants in commercial air-conditioning installations. As a result of mass production techniques, precipitators for air-conditioning installations are now available in "building block" cells providing capacities up to a million cubic feet per minute. Although these precipitators were developed principally for air-conditioning installations, their usefulness in the control of air pollution soon became known. One of the first units reported for the cleaning of process air was for removal of ceramic overspray in pottery glazing operations (Penney, 1937). Two-stage precipitators are widely used for re-

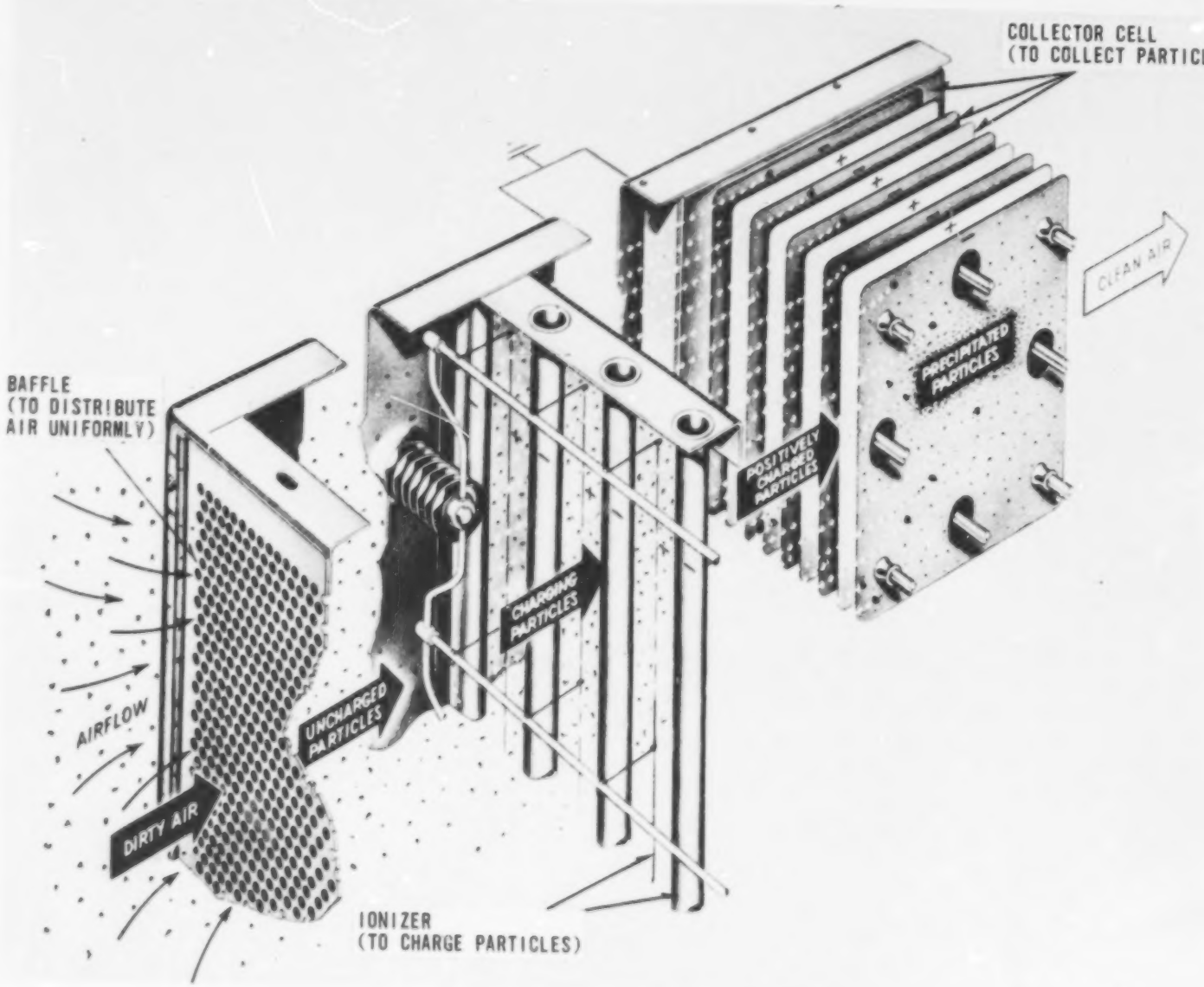


Figure 90. Components of standard two-stage precipitator (Westinghouse Electric Corporation, Hyde Park, Boston, Mass.).

moving oil mist created during operation of high-speed cutting or grinding tools. Precision manufacturing and electronic assembly areas are frequently equipped with precipitators to remove small quantities of dust and impurities from their environmental air. Hotels, restaurants, food-processing companies, and pharmaceutical manufacturers often use this method for cleaning circulating air. Another installation, shown in Figure 91, is designed to remove contaminants from the exhaust air of a meat-smoking operation.

THEORETICAL ASPECTS

Theory of Dust Separation

The physics of dust separation in a two-stage precipitator may best be understood by examining the stages separately. The function of the ionizing stage is to induce an electrical charge upon the particles in the airstream. When an electrical potential is applied between a wire and a grounded strut, as shown in Figure 92, an electric field is created that varies from a high strength near the wire to a low at the strut. When the potential is increased to the "critical corona voltage," local ionization of the airstream near the wire occurs and a blue corona is formed. Arcing or "sparkover" results if the voltage is further increased to a point where total ionization of the air between the electrodes occurs. This effects a short circuit, and the precipitator's efficiency drops correspondingly.

Below the corona's starting voltage or critical corona gradient, no ionization occurs and consequently no charging of particles takes place. The critical corona gradient, for round wires, is basically a function of wire size and condition. It may be determined by the equation

$$E_s = 30\,M\left(1 + \frac{0.30}{\sqrt{r}}\right) \qquad (78)$$

where

E_s = critical corona gradient, kv/cm

M = roughness factor, usually between 0.6 and 0.9

r = wire radius, cm.

The required potential may then be determined by

$$V_s = E_s\, r \ln \frac{4}{3}\frac{s}{r} \qquad (79)$$

where

V_s = corona starting voltage, kv

s = wire-to-strut spacing, cm.

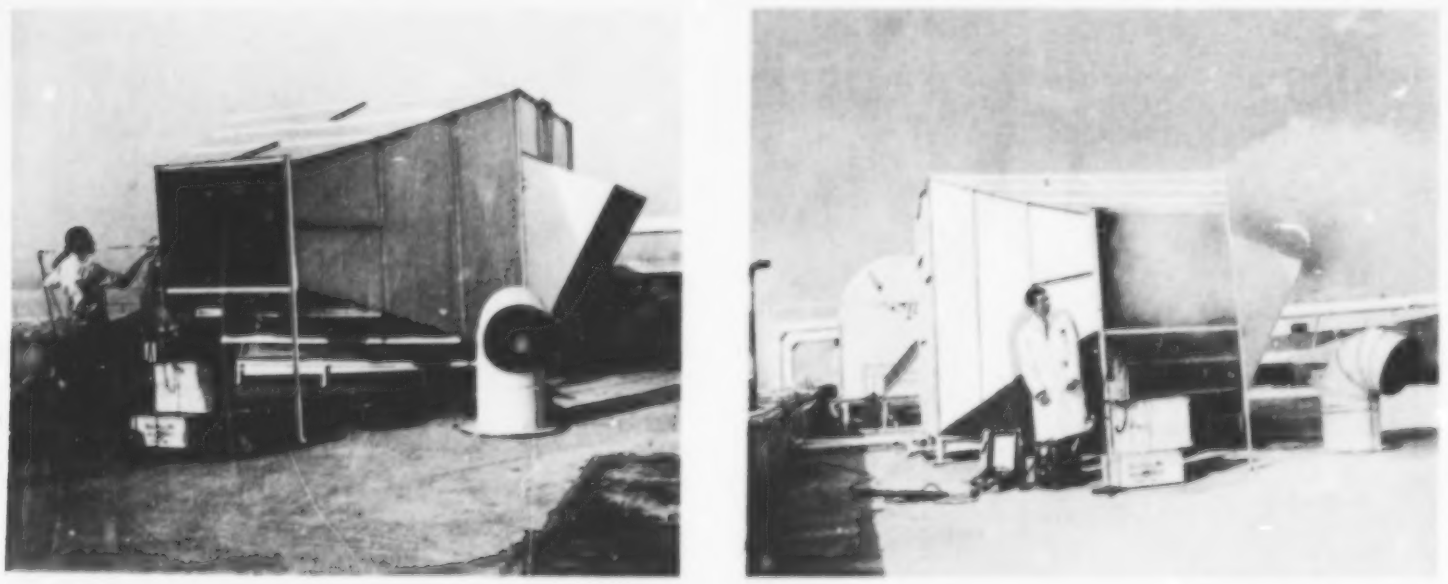


Figure 91. Two-Stage precipitator controlling smokehouse emissions: (left) precipitator on, (right) precipitator off (Luer Packing Co., Vernon, Calif.).

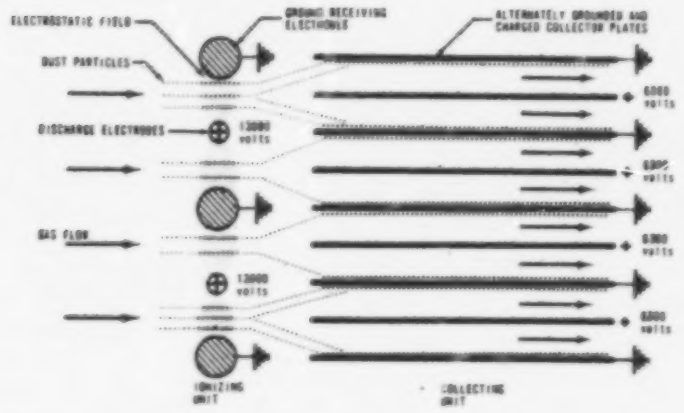


Figure 92. Schematic representation of two-stage precipitator principle (Perry, 1950).

Particle Charging

The degree of electrical saturation of the dispersed particles may be given, for a spherical conducting particle, by

$$n = \frac{3E a^2}{\epsilon} \cdot \frac{t}{t + \frac{1}{\pi N_o k \epsilon}} \qquad (80)$$

where

n = number of elementary electric charges acquired by a particle

E = electric field strength, stat volts/cm

a = particle radius, cm

t = time interval that particle is exposed to charging field, sec

N_o = ion density in charging zone, ions/cm^3

ϵ = charge on electron, 4.8×10^{-10} stat-coulomb

k = ion mobility, cm^2/sec-stat volt.

All units of this equation are expressed in the electrostatic centimeter-gram-second system. White has given the term $\frac{1}{\pi N_o \epsilon k}$ the notation of t_o, the particle-charging time constant, and states that it ranges from 10^{-1} to 10^{-4} seconds with charging normally effectively complete in about 10^{-2} seconds. The term $\frac{3E a^2}{\epsilon}$ is the limiting or saturation charge, n_s, for large values of time (White, 1951).

Equation 80 applies to particles greater than 0.5 micron in diameter, where charging is due primarily to ion bombardment. Charging by ion diffusion predominates for particles of about 0.1 micron and smaller in diameter and requires a somewhat different evaluation. Normally, neglect of the ultrafine particles in determining charging time introduces no significant errors because these particles represent a small weight fraction of the material being treated.

Drift Velocity

The charged particle reaching the collector section is acted upon by two vector forces--its momentum and the electrical attraction for the grounded or oppositely charged electrode. Additionally, the motion of the particle toward the electrode is retarded by viscous drag according to Stokes' law. The net velocity component toward the collecting electrode is termed the drift velocity, and is described by the equation

$$w = \frac{p E_c E_p a}{6 \pi \mu} \qquad (81)$$

where

w = drift velocity, cm/sec

E = electric field strength, stat volts/cm

μ = gas viscosity, poises

p = a constant.

The subscripts p and c represent precipitating and charging zones, respectively. Units are in the electrostatic cgs system. The equation may be modified by the Stokes-Cunningham correction factor for particles appreciably less than 1 micron in diameter, that is, approaching the mean free path between molecular collisions in air. For conducting particles, the constant p equals 3, and for nonconductors, p is a function of the dielectric constant and is usually between 1.5 and 2 (Rose and Wood, 1956).

Equation 81 illustrates the significance of the electrical field's strength in collection efficiency. The drift velocity varies with the product of the charging field and collecting field strengths. For this reason it is always advantageous to operate a precipitator at the maximum possible voltages without incurring excessive sparkover. Field strength is determined not only by impressed voltage

but by electrode configuration, dust loading, and other variables, so that a considerable degree of experience is needed to evaluate the drift velocity properly.

Efficiency

Determining the effectiveness of a device for control of atmospheric pollution is frequently difficult. When the airstream contains ultrafine particles, the increase in light transmittance may be important. In some cases the reduction in number of particles or the reduction in darkness of filter papers through which the air is passed may be significant. The normal method of determining efficiency of precipitators is by weight of material collected. The exponential Deutsch equation (Perry, 1950),

$$F = 1 - e^{\frac{-wA}{Q}} \qquad (82)$$

where

F = efficiency, decimal equivalent

A = collecting area, ft^2

Q = volumetric flow rate, cfs,

with appropriate units for drift velocity, has been developed primarily for application to single-stage precipitators. Penney (1937) presents the relationship for two-stage precipitators

$$F = \frac{wL}{vd} \qquad (83)$$

where

L = collector length, fps

d = distance between collector plates, ft

for units with close plate spacing. The exponential-type equation is frequently found applicable in practice. Walker and Coolidge (1953) have found the expression

$$F = 1 - \exp(-Kha)(V-V_s)\frac{L}{v} \qquad (84)$$

where

h = relative humidity, decimal equivalent

a = particle radius, μ

V = applied voltage, kv

K = a constant

to apply to both single- and two-stage precipitators collecting gypsum dust under laboratory conditions. The efficiency varies with the available voltage above the corona's starting voltage.

DESIGN FACTORS

Electrical Requirements

Normally, positive polarity in the ionizing section is used in two-stage precipitators since it is thought that less ozone and oxides of nitrogen are thus produced. With positive polarity, sparkover voltage is much closer to the critical corona voltage than is found with negative polarity. The practical operating voltage limit for standard units is about 18 kilovolts, with most operating at 10 to 13 kilovolts. Current flow under these conditions is small, 4 to 10 milliamperes. The collecting plates are usually activated at 5.5 to 6.5 kilovolts with precipitation's occurring on the grounded spacing plates. The actual current flow is very small since no corona exists between the plates.

In single-stage units recent developments have made available rather elaborate automatic control devices to maintain the maximum practical corona current. This type of control is not feasible for two-stage units. For some applications, however, manually adjusted rheostats have been used, and when a high degree of efficiency is required, the voltage can occasionally be adjusted to compensate for buildup of collected material.

Power consumption is a function chiefly of particle size, dust loading, voltage, and wire size. The actual power required for removal of a dust particle by precipitation is small compared with that for mechanical collectors because the energy is applied primarily to the particle only and not to the total gas stream. In practice, power requirements for standard two-stage precipitators are 15 to 40 watts per thousand cfm. The operating cost is, therefore, low.

High voltage is obtained by vacuum tube rectifying power packs that operate from a 110- to 120-volt a-c primary circuit. On small units one power pack may supply both ionizing and collecting sections. For larger volumes two or more power packs may be used in parallel for various groupings of ionizing cells with separate power packs for the collecting sections.

Air Capacity

Manufacturers normally rate these units at 85 to 90 percent efficiency by tests based on discoloration comparisons and at velocities between 300 to 600 fpm. For air-conditioning purposes these values are usually adequate, but for cleaning process air, a more thorough evaluation is necessary. Efficiency of cleaning for this latter purpose is usually based upon weight recovery and will likely be lower than by discoloration comparison.

Equation 83 determines efficiency to be directly related to air velocity. Equation 82, for units with constant collector area, relates velocity to efficiency by an exponential function. If dust particles move smoothly between the plates, collection efficiency is a function only of drift velocity and residence time. Penney assumes streamline flow through the precipitator, while recognizing that some turbulence occurs, in arriving at the required collector plate area for air-cleaning precipitators. Although 600 fpm is the limiting velocity for streamline flow in most two-stage units now being manufactured, mechanical irregularities reduce the permissible velocity. Figure 93 includes a graphical representation of equations 82 and 83 for data obtained on smokehouses.

It has been found that collection area is not always controlling. At a velocity of 300 fpm a dust particle is in the ionizing field only about 0.05 second, a very brief time when compared with 1.0 to 10 seconds for single-stage units. For some contaminants the increased efficiency at low velocity is the effect of increased ionization time rather than of streamline flow through the collector plates.

The degree of ionization may be increased by increasing the number of ionizing electrodes, either by decreasing spacing or by installing a second set of ionizing wires in series. Since decreased spacing reduces the allowable voltage without sparkover, use of the series arrangement appears advantageous. Decreased spacing has the advantage of lower first cost and lower space requirements.

Air Distribution

The distribution of the airstream entering the precipitator is as critical for high-efficiency two-stage operation as many other factors normally receiving more attention. A superficial velocity, the ratio of total airflow to precipitator cross-sectional area, is useful for equipment selection but may be misleading for close design. For conditions of low overall velocity of approximately 100 fpm, pressure drop through a precipitator is insignificant, and redistribution of high- or low-velocity areas of the airstream will not occur. Variations in airflow from 3 times average velocity to actual reverse flow have been observed in the vertical-velocity profile of these units for hot gas streams. Figure 93 shows that high velocity produces low efficiency while extremely low velocity does not result in compensating improvement. Overall efficiency is thus lowered. Two-stage precipitators are normally installed with horizontal airflow and frequently in positions requiring abrupt changes in direction of ductwork preceding the unit. Design such as this results in turbulent, uneven airflow. If air enters the precipitator plenum from an elbow or unsymmetrical duct, the air tends to "pile up" on the side of the precipitator opposite the entry.

Numerous methods are available for balancing the flow. A straight section of duct upstream eight duct diameters from the entry prevents transverse unevenness if a gradually diverging section precedes the precipitator. If this is not possible, mechanical means must be used. Turning vanes installed in an elbow or curve maintain a uniform distribution and also reduce pressure drop across the elbow, but do not balance flow satisfactorily. Baffles of various types or egg crate straightening vanes may be used in the transition duct. The most effective air-balancing device found consists of one or more perforated sheet metal plates that fully cover the cross-section of the plenum preceding the ionizers.

The sheet metal plates introduce an additional pressure drop that must be considered in the initial exhaust system design. A study of distribution in single-stage precipitators found that each subsequent plate installed in series added materially to flow uniformity (Randolph, 1956). It has also been indicated that, at low velocity, a perforated sheet immediately following the collector plates may in some cases be more effective than one preceding the ionizers. A sheet in this location also has the advantage of acting as an additional collecting surface for charged particles, though this effect is usually minor.

An open area of 40 percent for the perforated sheet has been found optimal, a range of 35 to 60 percent being generally adequate. Installations handling heated airstreams, above 100°F, at low velocities, require baffling to prevent high velocities at the top of the chamber due to thermal effects. In these cases a

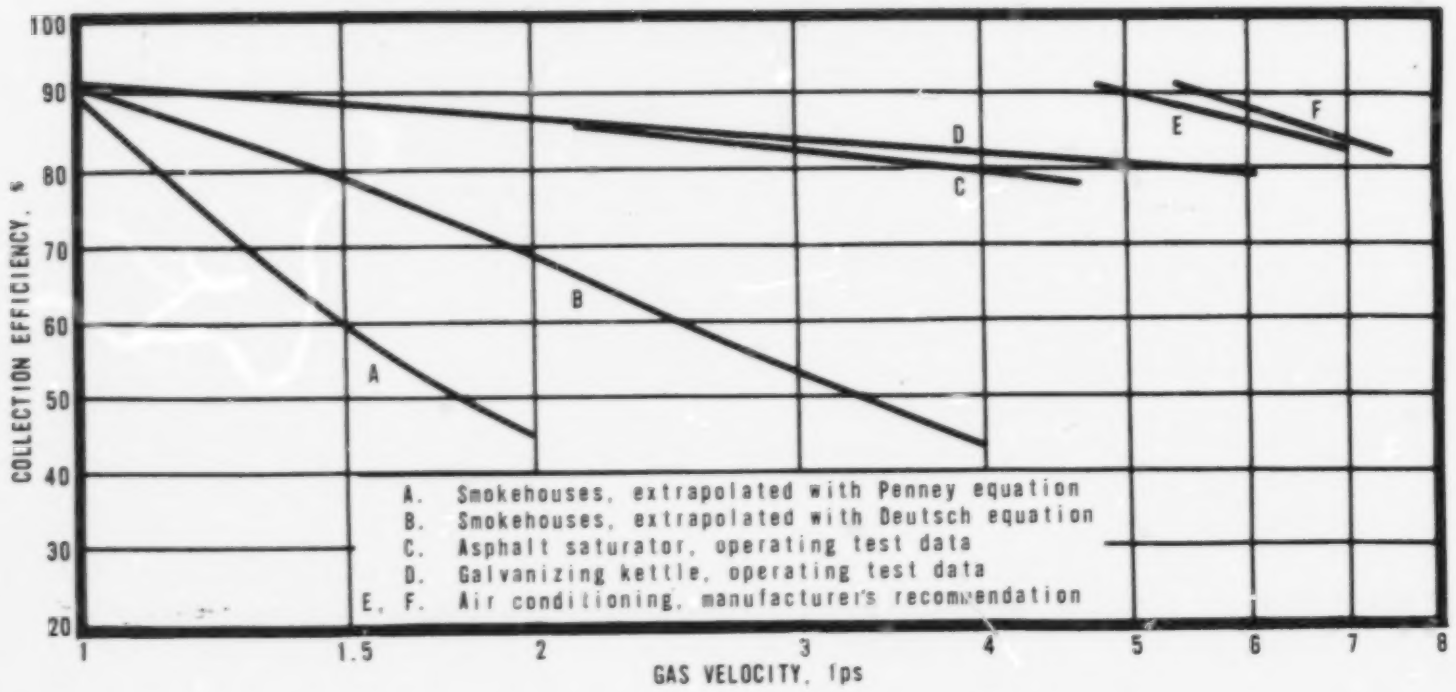


Figure 93. Efficiency of two-stage precipitator as function of velocity for several industrial operations.

perforated sheet covering only the upper half of the plenum preceding the ionizers may suitably equalize the flow. Vertical-flow precipitators are not affected by thermal conditions in this manner.

Auxiliary Controls

Two-stage precipitators have thus far not been extended to process exhaust gases with characteristics requiring unusual conditioning agents. Humidity adjustments, by water sprays or heating coils, are frequently used to modify electrical properties of the contaminants to a suitably conductive condition. For many materials, maintenance of greater than 50 percent relative humidity is advantageous. Under no condition, however, should the gas stream to the ionizer be saturated; reheating the airstream may be required to avoid saturation. Water droplets should be removed by mist eliminators preceding the ionizer to prevent excessive sparkover.

The collector plates and housing must be cleaned periodically. To keep this labor and downtime to a minimum, the use of precleaners is frequently recommended for the more easily removed contaminants. For dry materials a cyclone is usually adequate, though a simple scrubber is more commonly used, and the gas stream is thereby humidified. If fibrous materials such as cotton lint or synthetic fibres are entrained in the exhaust air, they must be prevented from reaching the precipitator where they may accumulate and bridge the plates, resulting in arcing and possible duct fires. Scrubbers and glass fiber filters have been successfully used to prevent problems such as this.

Particles charged in the ionizing section may sometimes have a drift velocity too low to be completely removed in the collector section. Operating the precipitator without oil on the collector plates and periodically blowing off the flocculated material may also be desirable. In either case the contaminants may precipitate in the exhaust system or be collected by an aftercleaner following the precipitator. Intentional use of this procedure is usually restricted to dry dusts such as carbon black or normal atmospheric dust. The aftercleaner may be a filter, cyclone, or scrubber as required by the specific process.

Air-conditioning installations are frequently equipped with automatic washing and recoiling devices. The aftercleaner then removes entrained water from the airstream and permits uninterrupted air circulation through the system.

CONSTRUCTION AND OPERATION

Assembly

Two-stage precipitators for capacities up to 20,000 cfm may be supplied by the manufacturer in completely preassembled package units requiring only external wiring and duct connections. For larger capacities or for heavy contaminant loading, a field-assembled model is supplied. This requires local fabrication of the precipitator housing with necessary drains, doors, baffles, and ductwork. Usually the ionizing and collection sections are assembled on one frame but they may be installed separately if desired. The installed weight of the precipitator is approximately 80 pounds per square foot for units with over 5 square feet of cross-sectional area. Usually, no additional foundation support is required for floor installations.

Smaller units may occasionally be adapted to fit into existing ducts or transition chambers of an exhaust system. If the precipitator vents to the outside atmosphere, a shield must be provided at the discharge side to protect it from weather elements.

Maintenance

Process air may contain approximately 2 grains of air contaminants per cubic foot in contrast to air-conditioning loads of 2 grains per 1,000 cubic feet. Because dusts and tars may not drain or fall off, they may impose a limitation of holding capacity on the collector. Since no rapping cycle is used on two-stage precipitators, the collected materials are held to the plates for relatively long periods of time and then washed down. The frequency of cleaning depends upon the quantity of contaminant collected, though cleaning cycles of 1 to 6 weeks are typical. Some installations are adaptable to automatic cleaning, but in most, the collector plates must be washed down manually or removed and washed in a tank. If a dry dust is being collected, the plates are usually recoated with oil by either dipping or spraying. When oils of low viscosity are collected, the oil drips or runs off and hence only occasional cleaning is needed to remove tars or gummy deposits.

Ionizer wires do not require frequent cleaning. These wires will, however, corrode slowly and must occasionally be replaced. Stainless steel wires rather than tungsten may be used if unusually corrosive conditions exist. The precipitator housing should be periodically washed to remove deposited contaminants. Since most standard precipitators are partially constructed of aluminum, uninhibited caustic cleaning solution must not be used. Cleaning time varies with the nature of the collected contaminant. Six to 12 man-hours per month may be considered average for a unit of 120 square feet cross-sectional area.

Safety

Standard units are carefully constructed to provide maximum electrical safety. At the low current used, accidents are not common, but normal high-voltage precautions must be observed. Interlocks between access doors and electrical elements should be used, and provisions for delayed opening after deenergizing are desirable to allow drainage of static charge.

The standard electrical systems are constructed to shut off automatically if a direct arc occurs. The inherent delay may, however, be sufficient to ignite an excessive accumulation of combustible oils or tars. It is advisable, therefore, to include automatic water sprinklers above the collection unit. The fire hazard is minimized by frequent cleaning if combustible contaminants are being collected. A precipitator is obviously not adaptable for use in exhaust systems handling vapors in explosive concentration.

APPLICATION

Among the types of operations that have been successfully controlled by standard two-stage precipitators are: (1) High-speed grinding machines, (2) meat product smokehouses, (3) continuous deep fat cookers, (4) asphalt saturators, (5) galvanizing kettles, (6) rubber-curing ovens, (7) carpeting dryers, and (8) vacuum pumps.

The emissions from all these operations include at least some oil mist. Oils, either mineral or vegetable, have a relatively high drift velocity and probably act as a conditioning medium for less conductive emissions. In addition, the oils deposited on the collector plates prevent reentrainment of collected dust or fumes. Organic substances between C_8 and C_{23} have been collected and, though showing some variation in resistivity, are usually precipitated in the first 3 to 6 inches of a collector plate. Velocity and ionization conditions that have been found adequate for air pollution control purposes are shown in Table 50.

Reentrainment of fumes from nonoiled plates does not always occur. On a galvanizing installation, ammonium chloride used in the flux is the largest constituent of the emissions.

Table 50. INDUSTRIAL OPERATION OF TWO-STAGE PRECIPITATORS

Contaminant source	Contaminant type	Ionizing voltage	No. of ionizer banks	Collector voltage	Efficiency, wt %	Velocity, fpm	Inlet concentration, grains/scf	Remarks
Tool grinding	Oil aerosol	13,000	1	6,500	90 (discoloration)	333	--	Manufacturer's recommendation
Meat smokehouse	Wood smoke Vaporized fats	13,000	2	6,500	90	60	0.103	Humidified and precleaned, 10-mil wire
Meat smokehouse	Wood smoke Vaporized fats	10,000	1	5,000	50	50	0.181	Ionizer wires at 1-1/2-in. spacing, poor air distribution
Galvanizing	Oil aerosol NH_4Cl fume	14,200	2	7,000	91	60	0.154	Second ionizer, 1-1/2-in. spacing, 15-mil wire
Deep fat cooking	Bacon fat Aerosol	13,000	2	6,500	75 (light transmittance)	68	--	Humidified and precleaned
Asphalt saturator (roofing paper)	Oil aerosol	12,000	1	6,000	85	145	0.384	Humidified and precleaned
Muller-type mixer	Phenol-formaldehyde resin	13,000	1	6,500	87	75	0.049	Odor not suitably reduced

During a test wherein fresh flux was added to the galvanizing kettle though no galvanizing was being done, ammonium chloride was found to be flocculated in the precipitator and then re-entrained in the exhaust air. During normal galvanizing operations this did not occur. An analysis of the materials collected in the precipitator showed that, during galvanizing, oil from the metal being galvanized is vaporized. Most of this is precipitated on the first few inches of the collecting plates, but a small quantity of the oil also precipitates with the ammonium chloride over the balance of the collecting area. The oil provides a medium for holding the dry fume to the plates. This effect is, of course, the reason for precoating the plates with oil in air-conditioning installations. The difference in precipitation rate of oil mist and ammonium chloride fume in the above example is illustrated in Figure 94.

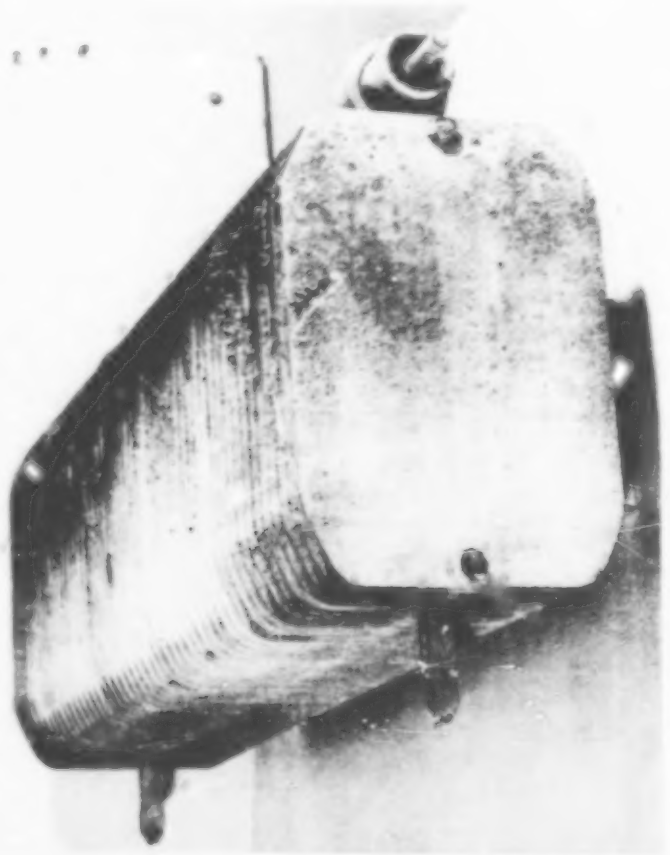


Figure 94. Precipitator collector plates showing rapid deposition of oil mist (dark area) compared with (light area) ammonium chloride fume (Advance Galvanizing Company, Los Angeles, Calif.).

Odors are frequently difficult control problems. When the odor is due to particulate matter, such as free fatty acids, the precipitator may be entirely adequate. This is frequently found to be the case with deep fat fryers. More commonly the odor source is both liquid aerosol and vapor, and the degree of control by a precipitator depends upon the relative odor strength of the two phases. For example, a precipitator intended to eliminate both odors and visible emissions from equipment blending hot phenolic resins with other material is not suitable with-

out additional control equipment. Phenolic resin dust is almost entirely removed from the exhaust stream by the precipitator. Since free phenol is present in both liquid and vapor form, however, the odors are not eliminated unless the temperature of the gas stream is low enough to condense most of the phenol. The vapor pressure of phenol at 220°F is about 5 times as great as it is at 160°F.

Two-Stage Precipitators of Special Design

The foregoing discussion has been primarily concerned with precipitators available from manufacturers as standard units. The theory is applicable, however, to less common units. Under some conditions, dust of high resistivity, above 10^{11} ohm-centimeters, causes ionization at the collecting surface of single-stage precipitators. A decrease in the sparkover voltage results, and the impressed high voltage may have to be decreased to prevent excessive sparking. The reduction may have to approach the critical corona voltage, and if so, the corona discharge and its resultant ionization diminish with a corresponding drop in collection efficiency.

Sproull (1955) describes a two-stage unit designed to circumvent this and other effects. For avoiding back ionization at the grounded electrodes in the ionization section, wider spacing between ionizing electrodes was used. Here negative ionization was used and at a correspondingly higher voltage owing to the wide spacing. For preventing reentrainment at the collector plates and minimizing ionization and sparkover, electrodes such as parallel sheets of expanded metal were found to perform more efficiently than the usual flat plate electrodes. Optimum results with this unit were obtained by using a 33-kilovolt reversing polarity potential on the collector section.

For standard units the limiting air velocity is less than 600 fpm. White and Cole (1960) described a two-stage precipitator designed for high-efficiency collection of oil aerosols at velocities between 2,000 and 6,000 fpm. The reentrainment of precipitated oil is prevented by use of a slotted tube drain fitted over the trailing edge of the collecting surface. Units such as these are designed and manufactured to very close tolerances to permit maximum electric field strength and the least airflow disturbance. In the unit described, collection voltage is held at 20 kilovolts while ionizing voltage is about 35 kilovolts. Negative ionizing polarity is used to provide a higher sparkover level. Collection efficiencies as high as 99.8 percent by light diffusion standards are reported on oil mists.

For continuous removal of collected contaminants, wetted film plates have been used in the collector section. Installations have been made in which the collection section has been replaced by a water scrubber, which presumably acts as a more efficient grounded electrode for some types of contaminants. Located after the collecting plates, a perforated plate on which a flowing film of water is maintained has been found to improve efficiency slightly. The wetted baffle plate alone is not equivalent to the effect of the normal collecting electrodes.

Sulfuric acid mist is efficiently collected by two-stage precipitators constructed of corrosion-resistant alloys. The Atomic Energy Commission (1952) reports 94 percent efficiency, by radioactivity-testing techniques, on acidic-cell ventilation gases but adds a qualifying statement that two-stage units are not recommended as the final cleaner on exhaust gases containing radioactive agents without thorough trial in a pilot stage.

Self-cleaning precipitators are available in which the collector plates are mounted on a chain belt, as shown in Figure 95. The plates are slowly passed through an oil bath that removes collected solids and reapplies an oil coating to prevent reentrainment. Another somewhat similar unit uses an automatically winding dry-filter medium to trap the collected materials. Cleaning requires only the occasional replacement of the filter medium roll.

Equipment Selection

The validity of the theoretical expressions has been well established for closely controlled small precipitators. The design of industrial units, however, invariably requires the use of empirical correction factors and approximations. An analysis of equations 78 through 82 shows several physical properties on which information is not readily available to industrial users. Particle size, for example, affects directly the limiting charge on the particle and affects, therefore, the calculated drift velocity and efficiency of separation. The actual size and distribution of oil droplets in an industrial exhaust stream is rarely determined. Similarly, the ionic current, which affects the field strength, cannot be accurately measured by ammeters because the observed values also reflect current leakage. For a small two-stage unit, ionic-current flow is small, and any leakage affects the total current very greatly.

Although operating costs of a precipitator are low, the units are considered as high-efficiency, high-cost control devices. A rule of thumb for industrial installations is about $1.00 per cfm for the installed equipment. When no precleaner is required and a package precipitator is ade-

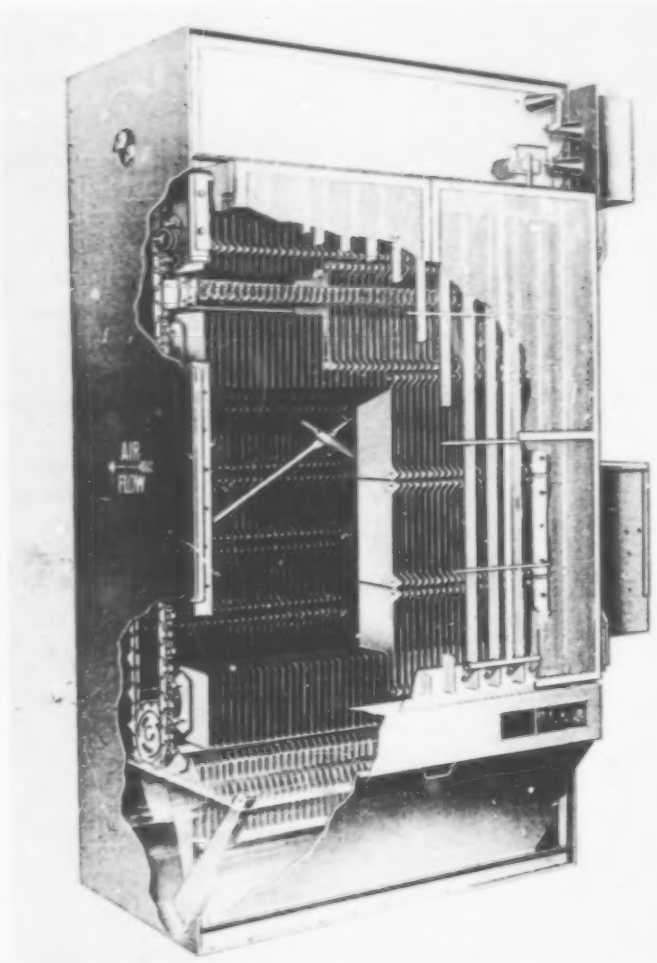


Figure 95. Automatic, self-cleaning, two-stage precipitator. Dust particles charged in the ionizing section are collected on aluminum plates. These are mounted on a motor-driven chain that automatically rinses and recoils the plates every 24 hours (American Air Filter Company, Louisville, Ky.).

quate, the cost may be as low as $0.25 per cfm excluding installation and ductwork. A difficult material to collect might require a precleaner, two ionizer banks, steam coil reheater and perforated baffle plates with an installed cost of about $2.00 per cfm.

Since many factors must be considered in designing or selecting a two-stage unit for a given process, some field experience with the characteristics of the air contaminant is necessary. In addition, a broad experience in precipitation work is essential. If data on the specific process to be controlled are lacking, then pilot or laboratory-scale information must often be obtained before a full-size unit is installed. Once the pertinent data have been collected, the general physical dimensions and electrical requirements of the precipitator can be determined by the equations previously discussed.

OTHER PARTICULATE-COLLECTING DEVICES

In addition to the devices already mentioned for the collection of particulate matter, there are other devices of more simple designs that have very limited application in the control of air pollution. These include settling chambers, impingement separators, and panel filters. Most are used principally as precleaners, but some are used as final collectors where the air contaminant is of large size or where the grain loading is very small, for example, paper filters for paint spray booths.

SETTLING CHAMBERS

Settling chambers are one of the simplest and earliest types of collection devices. The most common form consists of a long, boxlike structure in the exhaust system. The velocity of the dirty gas stream is reduced by the enlargement in cross-sectional area, and particles with a sufficiently high settling velocity are collected by the action of gravity forces. A very long chamber is required to collect small particles. Structural limitations usually restrict the usage of simple settling chambers to the collection of particles 40 microns or greater. Their greatest use is as a precleaner to remove coarse and abrasive particles for the protection of the more efficient collection equipment that follows the chamber.

If horizontal shelves are closely spaced within a settling chamber, the efficiency is greatly increased because particle-settling distances are reduced. A device such as this, known as a Howard dust chamber, was patented in 1908. It has a serious disadvantage in that the collected material is very difficult to remove from the shelves.

IMPINGEMENT SEPARATORS

When a gas stream carrying particulate matter impinges on a body, the gas is deflected around the body, while the particles, because of their greater inertia, tend to strike the body and be collected on its surface. A number of devices use this principle. The bodies may be in the form of plates, cylinders, ribbons, or spheres. An impingement separator element with staggered channels is shown in Figure 96.

Impingement separators are best used in the collection of mists. The collected droplets form a film on the surface and then gradually drip off into a collection pan or tank. Conversely, collected dry dust tends to become reentrained when

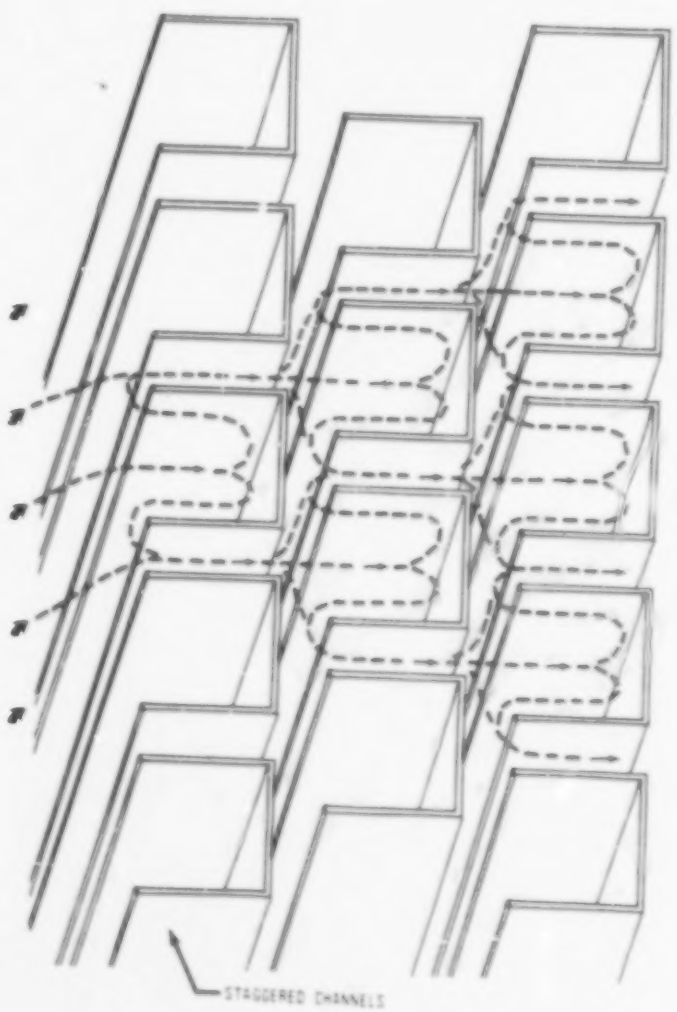


Figure 96. Impingement separator elements.

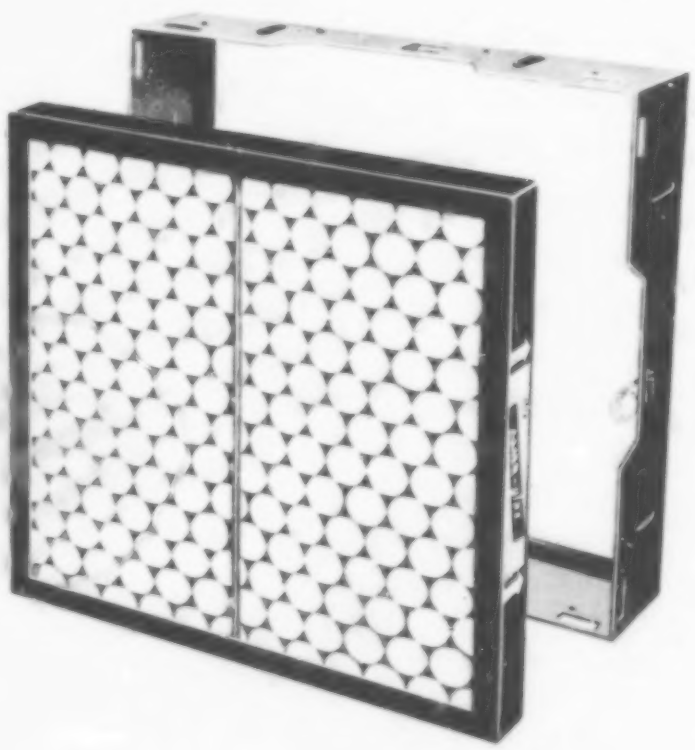


Figure 97. Panel filter (American Air Filter, Louisville, Ky.).

it falls off the collecting surface. For this reason, water sprays are sometimes used to wash off the collected dust.

PANEL FILTERS

Panel filters are most commonly used in air conditioning installations, though they do have several important industrial applications. Filters are supplied in units of convenient size, usually about 20 by 20 inches, to facilitate installation and cleaning. Each unit consists of a frame and a pad of filter material, as shown in Figure 97. The frames of similar units may be joined together to form a panel. These filters are classified into two types, viscous and dry.

Filters are called viscous because the filter medium is coated with a viscous material to help catch the dust and prevent reentrainment. The coating material is usually an oil with a high flash point and low volatility. The filter pad consists of materials such as glass fibers, hemp fibers, animal hair, corrugated fiberboard, split wire, or metal screening. When the maximum allowable dust load has accumulated, the metal trays are removed, washed or steamed, recoiled, and put back into service. Other pads are thrown away when they become loaded with dust as shown by their increased resistance to airflow. A common industrial application of the wire screen-type filter is found in collection of mist generated from cutting oils used by metal-cutting machines.

Dry filters are supplied in units similar to viscous filters, except that the depth is usually greater. The filter materials usually have smaller air passages than the viscous filters do, and hence, lower air velocities must be used to prevent excessive pressure drop. Dry filters are usually operated at 30 to 60 fpm, as contrasted with 300 to 500 fpm for viscous filters. In order to increase the filtering area per unit of frontal area, the filter pads are often arranged in an accordian form with pleats and pockets. When the pressure drop becomes excessive because of accumulated dust, the dry-type pads are discarded. Dry filters are frequently used to collect the overspray from paint-spraying operation.

PRECLEANERS

Devices of limited efficiency are often used ahead of the final cleaner. If the gases contain an appreciable amount of hard, coarse particles, a precleaner can materially reduce erosive wear on the more efficient (and more expensive) final collector. If the collected material has value, a precleaner, for example, one ahead of a scrubber, can sometimes collect the bulk of it in a more usable form. Devices usually used as precleaners are settling chambers and centrifugal separators.

CHAPTER 5

CONTROL EQUIPMENT FOR GASES AND VAPORS

AFTERBURNERS

HOWARD F. DEY, Air Pollution Engineer

BOILERS USED AS AFTERBURNERS

WILLIAM L. POLGLASE, Air Pollution Engineer

ADSORPTION EQUIPMENT

MARC F. LeDUC, Air Pollution Engineer

VAPOR CONDENSERS

ROBERT T. WALSH, Senior Air Pollution Engineer*

ROBERT C. MURRAY, Senior Air Pollution Engineer

GAS ABSORPTION EQUIPMENT

HARRY E. CHATFIELD, Air Pollution Engineer

RAY M. INGELS, Air Pollution Engineer†

*Now with the National Center for Air Pollution Control, Public Health Service, U.S. Department of Health, Education, and Welfare.

†Now with State of California Vehicle Laboratories, Los Angeles, California.

BLANK PAGE

CHAPTER 5

CONTROL EQUIPMENT FOR GASES AND VAPORS

AFTERBURNERS

Afterburners are used as air pollution control devices for a large variety of industrial and commercial equipment. Whenever the equipment releases combustible aerosols, gases, or vapors into the atmosphere, an afterburner can frequently be used to control these emissions for compliance with air pollution control regulations. Opacities of visible emissions can be reduced or eliminated, the concentrations of particulate matter can be reduced, or nuisances can be abated through their use. In some installations it is possible to reclaim a portion of the sensible heat from the afterburner discharge gases and thereby reduce the cost of operation.

Two types of afterburners are in current use: Direct fired and catalytic. The direct-fired type is much more commonly employed because of greater adaptability and lower first cost as compared with the catalytic type. Nevertheless, catalytic afterburners appear to be useful for control of some processes whereby organic vapors are emitted. The use of a catalyst promotes some combustion reactions at lower temperatures than those normally required by direct-fired afterburners. The operating temperatures of catalytic afterburners may thus be lower than those of the direct-fired type used for the same service, and lower fuel costs are sometimes possible through their use.

When incomplete combustion occurs in any afterburner, odor concentrations are not reduced and, at times, are actually increased across the afterburner. To overcome this defect, incineration at higher temperatures with adequate oxygen is required. In some cases, because of materials of construction, catalytic afterburners cannot be operated at temperatures necessary to produce complete combustion. In cases where temperatures of 1200°F or more are required, there appears to be little inducement to install the higher priced catalytic unit since a well-designed direct-fired unit will usually be adequate.

DIRECT-FIRED AFTERBURNERS

Direct-fired afterburners have proved capable of controlling combustible emissions from many kinds of industrial and commercial equipment. Indeed, they are the most commonly used air pollution control devices where emissions of combustible aerosols, vapors, gases, and odors are emitted. Equipment successfully controlled include aluminum chip driers, animal blood driers, asphalt-blowing stills, automotive brake shoe-debonding ovens, citrus pulp driers, coffee roasters, electric insulation burnoff ovens, flue-fed refuse incinerators, foundry core ovens, meat smokehouses, paint-baking ovens, rendering cookers, varnish cookers, and other equipment operated within similar temperature ranges.

Specifications and Design Parameters

The principal components of a direct-fired afterburner are the combustion chamber, gas burner, burner controls, and temperature indicator. The afterburner chamber is generally cylindrical and constructed of firebrick or castable refractory with a sheet iron shell. For most afterburner installations, Class 27 castable refractory and high-duty firebrick are satisfactory since average gas temperatures seldom exceed 2,000°F. The afterburner chamber must be designed for complete mixing of the contaminated gases with the flames and the burner combustion gases. One satisfactory method of achieving this appears to be the admission of the contaminated gases into a throat where the burner is located. Sufficiently high velocities may be obtained here for thorough mixing of the gases with the burner combustion products in the region of highest temperature. Gas velocities in the afterburner throat of 15 to 25 fps are found adequate. A retention time of 0.3 to 0.5 second for the gases within the afterburner, and operating temperatures of 850°F to 1,500°F have been found satisfactory for most installations. High efficiencies are normally achieved at the higher operating temperatures. Figure 98 illustrates a typical direct-fired afterburner in sectional view.

An exhaust fan is used to deliver the contaminated gases to the afterburner when natural draft is inadequate. This fan may be an axial-flow or squirrel cage type since the dust resistance of the exhaust system installed is usually low.

Several types of gas burners have been used successfully. Among these are: Atmospheric, nozzle mixing, pressure mixing, premixing, and multijet gas burners. Many arrangements

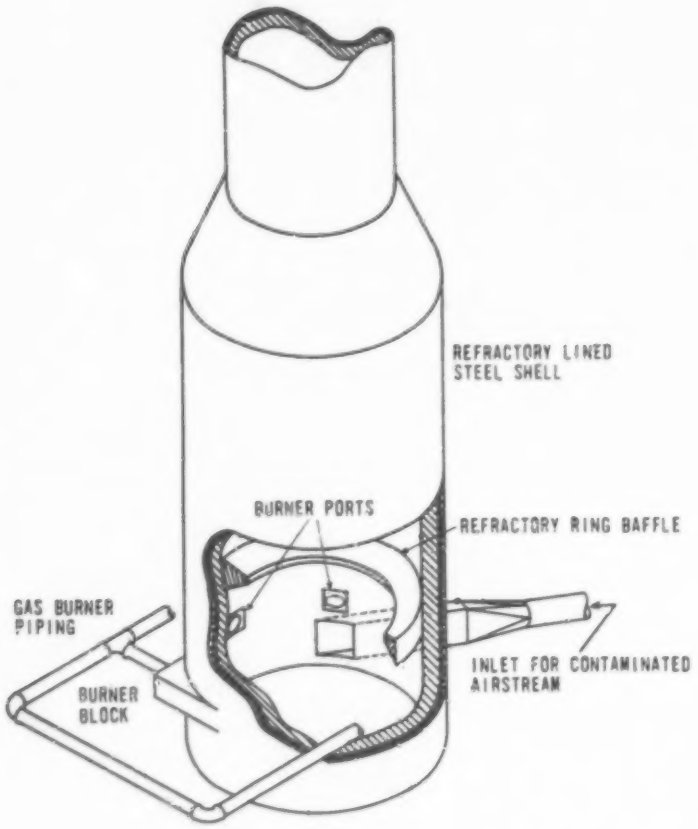


Figure 98. Typical direct-fired afterburner with tangential entries for both the fuel and contaminated gases.

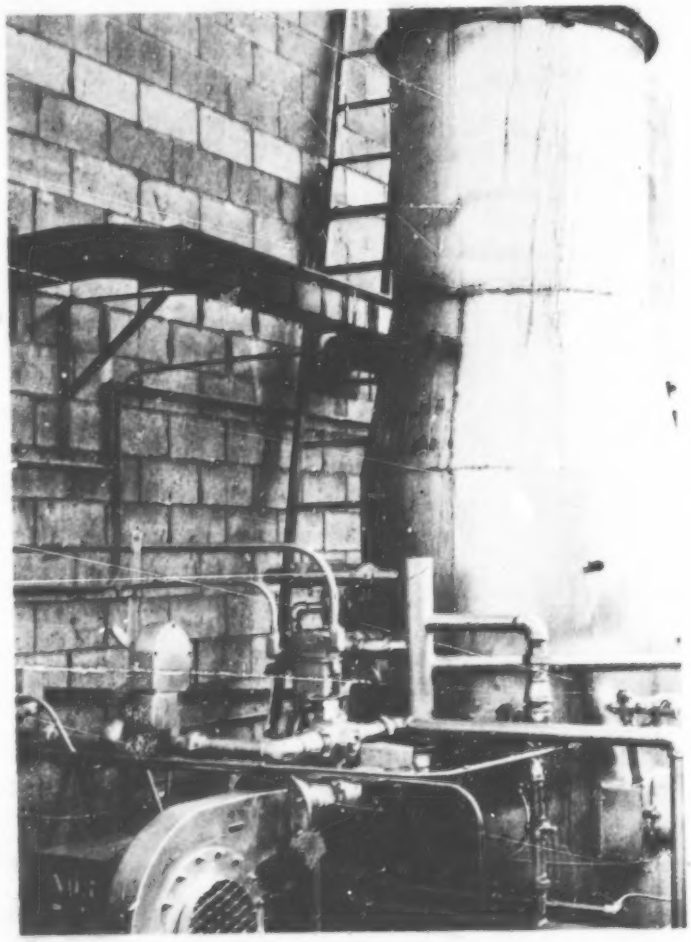


Figure 99. Direct-fired afterburner venting three varnish-cooking kettles (Standard Brand Paint Co., Torrance, Calif.).

of burners in afterburner chambers are possible. The burner should be positioned to provide complete mixing of the contaminated gases with the burner combustion gases. In addition, sufficient oxygen must be available to burn all air contaminants completely. The gas burner should be located near the entrance into the afterburner for the contaminated gases. One or more burners firing tangentially into the base of a cylindrical afterburner chamber have been used advantageously. Figures 99, 100, 101, and 102 illustrate afterburners with this type of burner arrangement. Multijet and multinozzle burners located in the base of an afterburner chamber have also been used. Figure 103 shows an afterburner with this burner arrangement. The latter arrangement appears to provide better mixing of contaminated gases with burner combustion gases and consequently greater afterburner efficiencies. Afterburners have been constructed that use multijet gas burners in which all combustion air is supplied by the contaminated gases, and thus minimum fuel requirements for a specific temperature are provided. An afterburner of this type is shown in Figure 104. An afterburner using a single-inspirator gas burner is shown in Figure 105. Burners having long, luminous flames appear to incinerate contaminants more effectively than those having short, nonluminous flames. This is probably due to more effective mixing of the contaminated gases with the burner combustion gases and greater heat transfer by radiation. Long, luminous flames may be created if the mixing of the gas and air is so slow that burning is completed at a considerable distance from the burner (North American Combustion Handbook, 1952).

Many direct-fired afterburners have only flame failure controls. The installation of modulating gas burner controls may effect considerable savings in fuel where the volume of gases or the amount of combustible material delivered to the afterburner varies appreciably during the process cycle, or where both vary. A constant temperature in the afterburner chamber can be maintained through a gas temperature sensing element that actuates the burner input control. When, however, the volume of contaminated gases and the amount of combustible materials re-

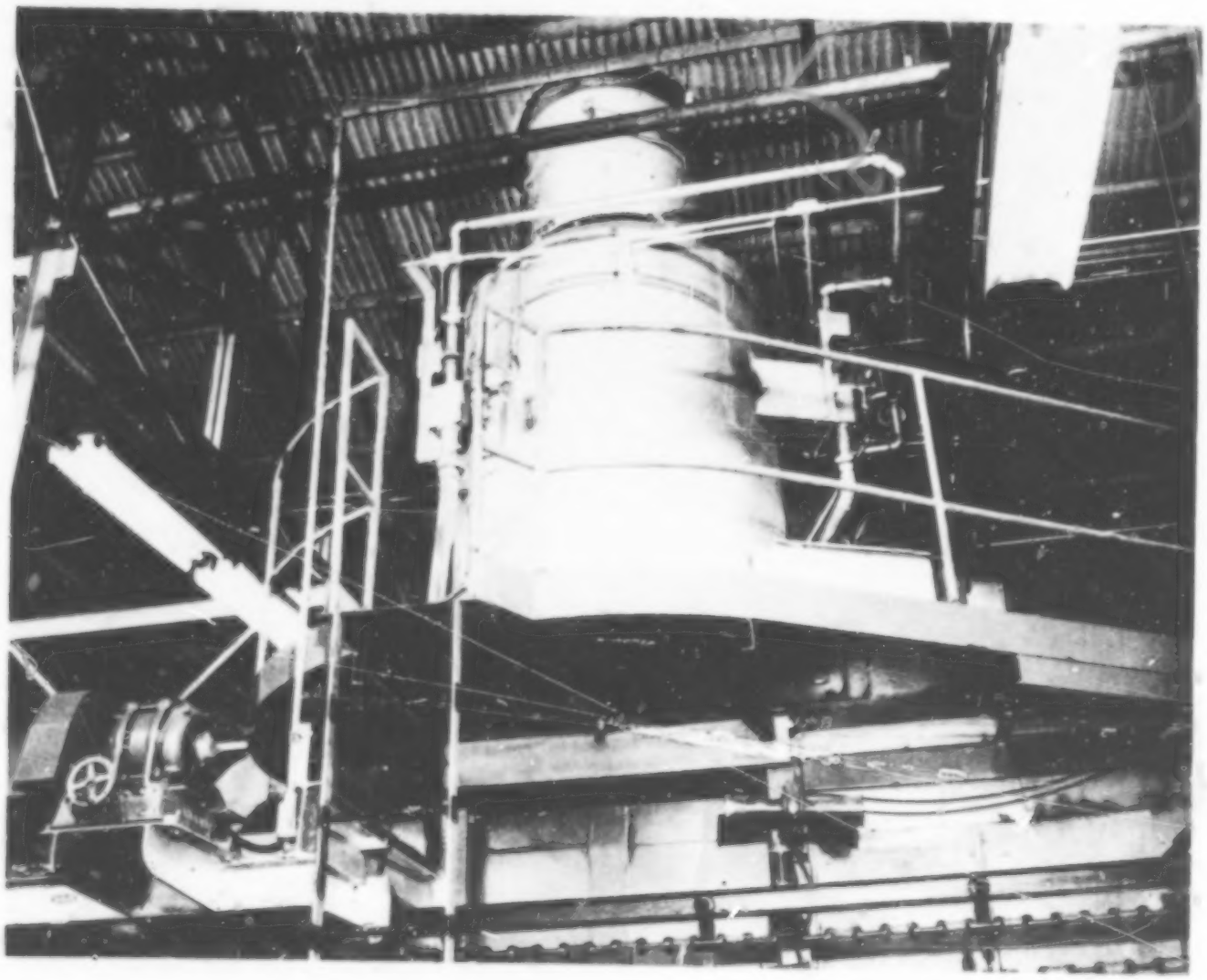


Figure 100. Direct-fired afterburner controlling emissions from a paint-baking oven (Rheem Mfg. Co., Southgate, Calif.).

main relatively constant, the firing of the burner at a fixed rate seems preferable.

An indicating- or recording-type temperature-measuring device is usually installed to show the afterburner's operating temperature at all times. A bare thermocouple is normally used because of low cost and rapid response to temperature changes. The thermocouple should be located near the top of the afterburner chamber to avoid large errors produced by direct radiation from the burner flames. The thermocouple may be installed in a thermocouple well for protection.

A safety pilot is usually provided to shut off the burner gas supply if the main burner malfunctions or the flow of contaminated gases to the afterburner is interrupted. It may also be advisable to install a high-temperature-limiting control to shut off the gas burner fuel supply if the flow of contaminated gases to the afterburner is interrupted.

Operation

Operation of direct-fired afterburners is relatively simple. The contaminated gases are delivered to the afterburner from the process equipment by the exhaust system. The contaminated gases are mixed thoroughly with the flames and the burner combustion gases in the afterburner throat. Next, the gases pass into the main section of the afterburner where velocity is reduced somewhat by the larger cross-sectional area. Here the combustion reactions are completed and the incinerated air contaminants and combustion gases are discharged to the atmosphere. Although the mechanics of most combustion reactions are doubtlessly complicated, conditions must be provided that will most nearly incinerate all the air contaminants to carbon dioxide and water vapor.

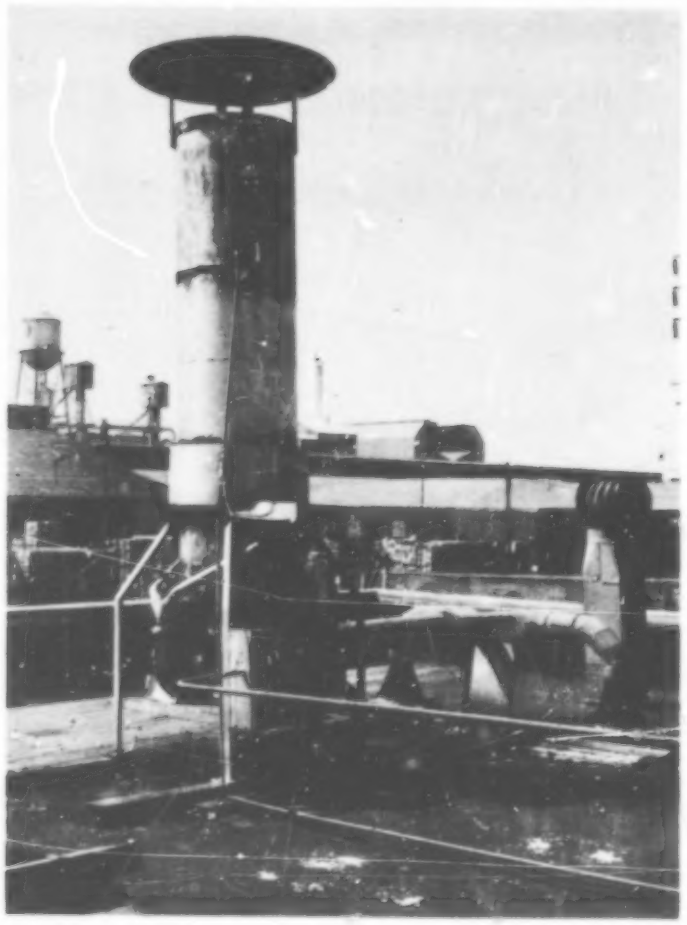


Figure 101. A direct-fired afterburner controlling emissions from two recirculating-type meat smokehouses (High Standard Meat Co., Los Angeles, Calif.).

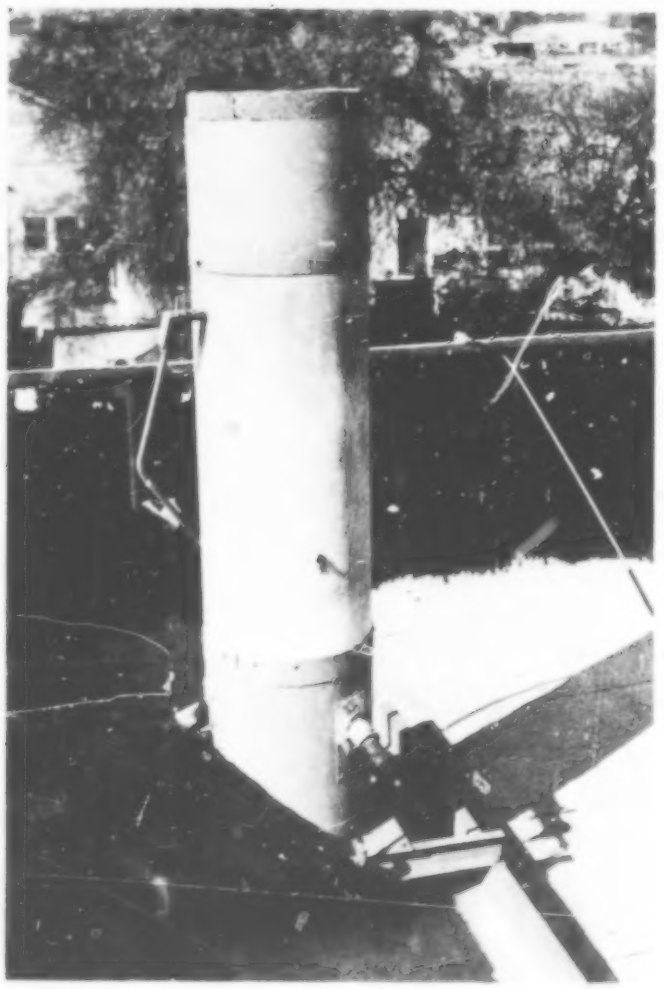


Figure 102. Direct-fired afterburner controlling emissions from a plastic-curing oven (Industrial Rock, Glendale, Calif.).

Efficiency

Efficiency of direct-fired afterburners depends on several variables, namely, the degree of mixing of the contaminated gases with the flames and burner combustion gases within the afterburner chamber, operating temperature, retention time of the gases within the afterburner, and concentration and types of contaminants to be burned.

Design calculations

The following example illustrates some of the factors that must be considered in the design of a direct-flame afterburner.

Example 21

Given:

A direct-fired afterburner is to be installed to incinerate the air contaminants discharged from meat smokehouses and eliminate visible emissions and odor. The maximum rate of discharge has been determined to be 1,000 scfm at 150°F. Assume the effluent gases have the same properties as air. (Consideration of the enthalpies and specific heats of the individual gaseous components of the contaminated gas stream will show this to be a reasonable assumption. Any corrections would introduce an insignificant refinement to the calculations when considered with respect to the overall accuracy required. Nevertheless, there will be situations where the contaminated gases contain a sufficient quantity of a combustible gas or vapor to make necessary the calculation of its heat of combustion and consequent enthalpy and temperature increase of the afterburner gases.)

Problem:

Determine the design features of a direct-flame afterburner to incinerate the contaminated gases.

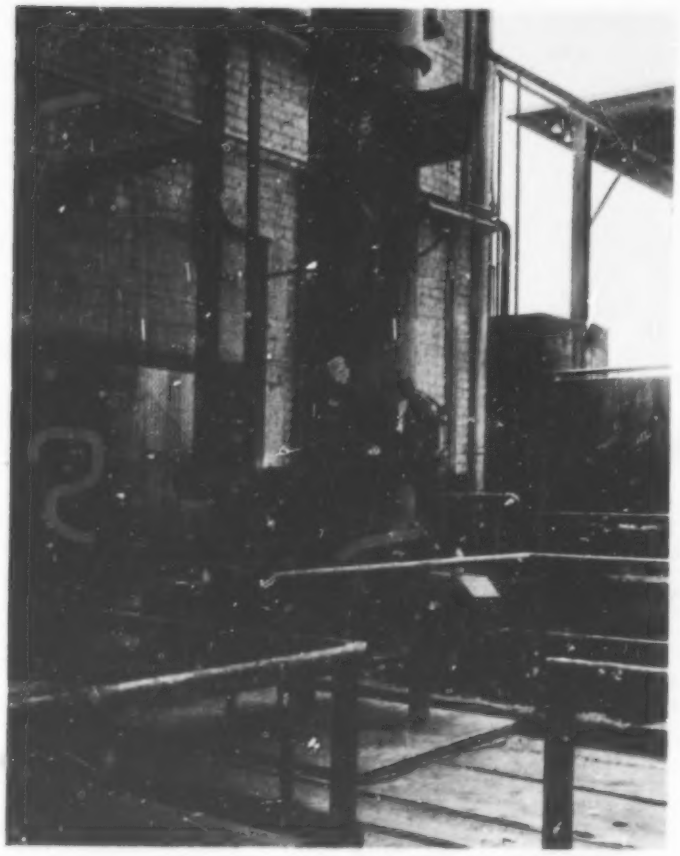


Figure 103. Direct-fired afterburner controlling odorous emissions from animal matter-rendering equipment (Peterson Manufacturing Co., Inc., Los Angeles, Calif.).

Figure 104. A direct-fired afterburner controlling emissions from five meat smokehouses (Packers Central Loading Co., Vernon, Calif.).

Solution:

1. Mass flow rate of contaminated gases:

$$\frac{(1,000 \text{ cfm})(60 \text{ min/hr})}{13.1 \text{ ft}^3 \text{ air/lb air}} = 4,580 \text{ lb/hr}$$

2. Heat required to increase the temperature of the gases from 150° to 1,200°F:

   An operating temperature of 1,200°F for an afterburner has been found sufficient to incinerate air contaminants emitted by meat smokehouses.

   Enthalpy of gas at 1,200°F = 287.2 Btu/lb (see Table D3, Appendix D)

   Enthalpy of gas at 150°F = 21.6 Btu/lb

   Δh = 265.6 Btu/lb

   (4,580)(265.6) = 1,216,000 Btu/hour

3. Heat losses from afterburner due to radiation, convection, and conduction:

   A quantity equal to 10 percent of item No. 2 will be assumed. This is a conservative

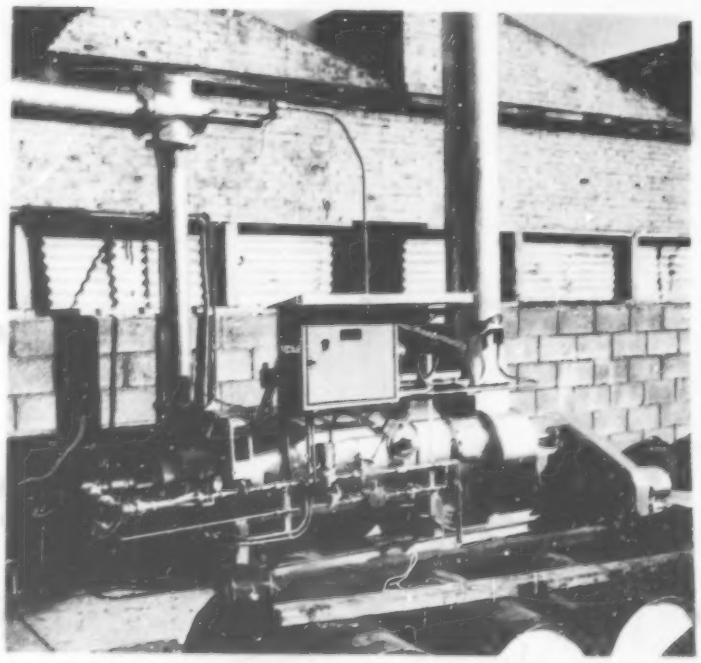


Figure 105. Direct-fired afterburner venting three varnish-cooking kettles and a thinning station (National Paint and Varnish Co., Los Angeles, Calif.).

estimate for afterburners constructed of firebrick or castable refractory and operated at normal temperatures.

$$(1,216,000)(0.10) = 121,600 \text{ Btu/hour}$$

4. Total heat required by afterburner:

$$1,216,000 + 121,600 = 1,338,000 \text{ Btu/hour}$$

5. Required natural gas volume capacity of burner:

The contaminated gases from many types of equipment contain sufficient oxygen to furnish at least the excess needed for proper combustion of the natural gas supplied to the burner. Smokehouses are considered to be this type of equipment. The natural gas will, therefore, be assumed to be supplied with theoretical air at the burner and with excess air from the smokehouse gases.

Gross heating value of natural gas taken at 1,100 Btu/ft^3.

Net heat available at 1,200°F from the burning of 1 ft^3 of natural gas with theoretical air is 721.3 Btu/ft^3 (see Table D7 in Appendix D).

$$\frac{1,338,000}{721.3} = 1,854 \text{ ft}^3\text{/hour}$$

6. Volume rate of gas burner combustion products at 1,200°F:

With theoretical air, 1 ft^3 of natural gas yields 11.45 ft^3 of products of combustion (see Table D7 in Appendix D).

$$\frac{(1,854)(11.45)(1,200 + 460)}{(3,600)(60 + 460)} = 18.83 \text{ ft}^3\text{/sec}$$

7. Volume rate of contaminated gases at 1,200°F:

$$\frac{(1,000)(1,200 + 460)}{(60)(60 + 460)} = 53.2 \text{ ft}^3\text{/sec}$$

8. Total volume rate of gases in afterburner at 1,200°F:

$$18.83 + 53.2 = 72.0 \text{ ft}^3\text{/sec}$$

9. Diameter of afterburner throat:

Throat velocities of 15 to 25 ft/sec have been found to provide adequate mixing of contaminated gases with flames of burner combustion products. Use a design velocity of 20 ft/sec.

$\frac{72.0}{20} = 3.60 \text{ ft}^2$, ∴ Use throat diameter of 25-1/2 in.

10. Diameter of afterburner combustion chamber:

Combustion chamber velocities of 10 to 15 ft/sec have been found high enough to provide adequate turbulence for completing combustion and allowing the construction of an afterburner of reasonable length for recommended residence time of 0.3 sec. Use a design velocity of 12 ft/sec.

$\frac{72.0}{12} = 6.00 \text{ ft}^2$, ∴ Use chamber diameter of 33 in.

11. Length of afterburner combustion chamber:

Use a ratio of afterburner combustion chamber length-to-diameter of 2. This ratio appears to be a reasonable minimum for the velocities used and will provide adequate residence time of the gases in the combustion chamber.

$$(2)(33) = 66 \text{ in.}$$

12. Retention time of gases in afterburner combustion chamber:

$$\frac{5.5 \text{ ft}}{12 \text{ ft/sec}} = 0.46 \text{ sec}$$

This is satisfactory. Experience indicates that a retention time of 0.3 sec at 1,200°F is sufficient for the incineration of nearly all types of combustible air contaminants.

Results of several tests of direct-fired afterburners are presented in Table 51. The process equipment and the afterburners in each of these tests are briefly discussed.

Test C-319

The afterburner in test C-319 and in test C-725 was installed to reduce the discharge of excessive particulate matter and eliminate odor and opacity of emissions from the operation of varnish-cooking kettles. Aerosols, vapors, and odors from the operation of three varnish cooking kettles and one kettle-cooling station are vented by an exhaust system to a direct-fired afterburner preceded by a water spray leg. The water spray leg functions as a

Table 51. STACK ANALYSES OF EMISSIONS FROM DIRECT-FIRED AFTERBURNERS

Test series No.[a]	C-319	C-725	C-462	C-566	C-318	C-729
Process equipment[a]	Three varnish-cooking kettles	Three varnish-cooking kettles	Five meat smokehouses	Five meat smokehouses	Paint bake oven	Phthalic annydride production unit
Burner type	Four nozzle mixing	One inspirator	One pressure mixing	One multijet	Three nozzle mixing	One multijet
Afterburner combustion chamber temp, °F	1,220	1,200	630	850	1,520	1,200
Inlet gas volume, scfm	950	200	305	1,600	1,400	3,800
Outlet gas volume, scfm	1,300	920[b]	500	2,000	1,800	6,400
Particulate matter, lb/hr, inlet	5.20	5.70	0.52	1.66	0.40	20.0
Particulate matter, lb/hr, outlet	0.31	0.20	0.57	0.56	0.09	1.0
Control efficiency, %	91	96	-10	66	78	95
Organic acids, lb/hr, inlet	1.41	0.24	0.24	1.88	--	29
Organic acids, lb/hr, outlet	0.73	0.00	0.00	0.27	--	0.88
Aldehydes, lb/hr, inlet	0.30	0.29	0.04	0.49	0.19	1.75
Aldehydes, lb/hr, outlet	0.11	0.02	0.06	0.22	0.03	0.43

[a] The process equipment was controlled for the following reasons:
1. Excessive opacity of emissions (C-462 and C-566).
2. Excessive emission of particulate matter (C-318).
3. Excessive opacity of emissions and excessive emission of particulate matter (C-319, C-725, and C-729).

[b] Volume includes admission of dilution air to exhaust fan.

precleaner in which the contaminated gas stream is cooled to provide some condensation of vapors. The water sprays also remove larger particles of mists and solids and provide flashback control.

The afterburner is a vertical cylinder tangentially fired at the base by four nozzle mixing gas burners as shown in Figure 99. The contaminated gas stream enters the afterburner tangentially opposite the burners.

Test C-725

The basic equipment and process in test C-725 are essentially the same as in test C-319. In this installation, however, there is no water spray leg. The afterburner consists of a horizontal cylinder fired at one end by an inspirator-type gas burner as shown in Figure 105. The contaminated gas stream enters the afterburner tangentially adjacent to the burner. The entire system is placed under negative pressure by an exhaust fan located at the afterburner outlet.

The afterburner in this test and the one in test C-319 show high efficiency in the incineration of particulate matter.

Test C-462

Emissions of excessive opacity were abated by the afterburner described in test C-462 and in test C-566. The smoke and gases from five natural-draft-type meat smokehouses are vented through ductwork to a direct-fired after burner. The afterburner is a vertical cylinder fired tangentially at the base by a pressure mixing gas burner. The contaminated gases enter the afterburner axially at the base.

Intermittent emissions were visible from the afterburner during the test. Efficiency in the incineration of particulate matter was negative. This appeared to be due primarily to the unusually low afterburner temperature. The visible component of the smokehouse gases was apparently vaporized in the afterburner, which rendered it invisible. Nevertheless, there was no condensation downstream from the afterburner to form a visible plume. The afterburner was satisfactory for abating the excessive opacity of emissions from the smokehouses.

Test C-566

The basic equipment and process in test C-566 are virtually the same as those in

test C-462. The afterburner is a vertical cylinder with an upshot multijet gas burner located at the base as shown in Figure 104. The smokehouse gases are conveyed to the afterburner by an exhaust fan. One unusual feature of this afterburner is that all oxygen for combustion of the fuel gas is obtained from the contaminated gas stream.

This afterburner was reasonably efficient at a relatively low temperature, and no visible emissions were detected during the test.

Test C-318

An afterburner was installed to reduce the concentration of particulate matter in the oven exhaust gases to allowable limits. Metal drums are spray painted with epon-phenolic and oleoresinous coatings and are baked at 420°F in a conveyorized gas-fired, recirculating-type paint bake oven. A portion of the gases containing several solvents is vented to an afterburner. The remainder is recirculated from the heaters to the oven. The afterburner consists of a vertical cylinder with three nozzle mixing gas burners located around its circumference as shown in Figure 100. The contaminated gases enter the afterburner tangentially and the burners fire the unit in a similar manner.

The afterburner's operating temperature of 1,520°F during the test was higher than usual. Previously an operating temperature of 1,410°F had appeared satisfactory for control of emissions from the oven.

Test C-729

An afterburner was installed to reduce the excessive concentration of particulate matter and eliminate excessive opacity of emissions from a phthalic anhydride production unit. Phthalic anhydride is produced by a catalytic oxidation process. The gases discharged contain phthalic anhydride, naphthalene, benzoic acid, naphthaquinone, and other reaction products. These gases are vented to a settling chamber and direct-fired afterburner. The afterburner is a vertical cylinder with a multijet gas burner located in the upper section as shown in Figure 106. The contaminated gases enter the afterburner tangentially near the burner and pass downward through the unit. An exhaust fan is located at the afterburner outlet.

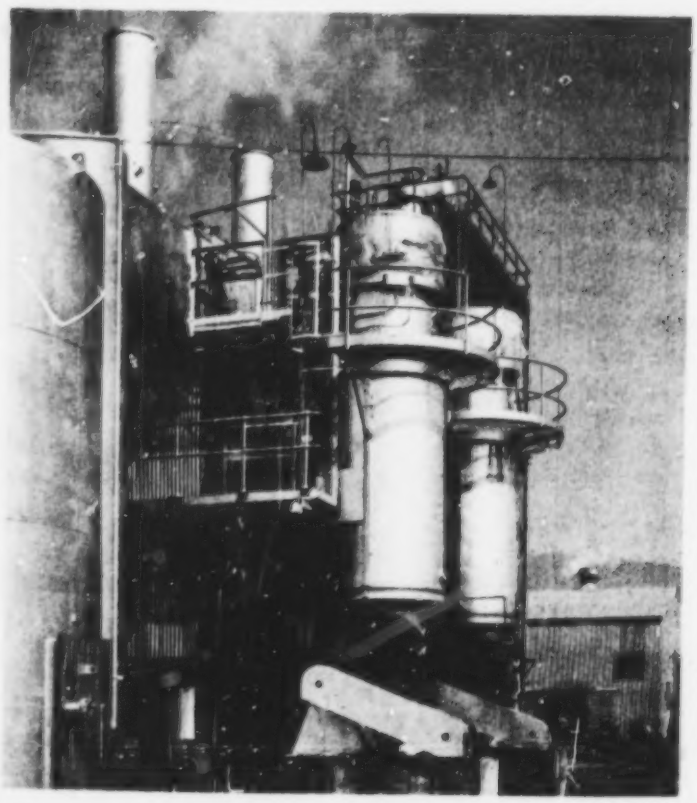


Figure 106. Emissions from two phthalic anhydride production units being controlled by direct-fired afterburners (Reichhold Chemicals, Inc., Azusa, Calif.).

Efficiency in the incineration of particulate matter was high. Determination of the odor threshold of afterburner inlet and outlet gases indicates an odor reduction efficiency of 97 percent.

Installation costs

A survey of installation costs of direct-fired afterburners reveals a general range of $5.00 to $10.00 per scfm contaminated gas.

CATALYTIC AFTERBURNERS

Catalytic afterburners have found their greatest use in the control of solvent and organic vapor emissions exhausted from industrial ovens. These emissions are created in metal-decorating and metal-coating ovens, foundry core ovens, wax burnout ovens, fabric-backing and fabric-coating ovens, and ovens for the baking of the binder in the production of rock wool batts. Some typical catalytic afterburners are shown in Figures 107, 108, 109, and 110.

Specifications and Design Parameters

Basically, a catalytic afterburner consists of the afterburner housing containing a preheating

Figure 107. Catalytic afterburners controlling emissions from fabric-coating baking ovens (Western Backing Corporation, Culver City, Calif.).

section (if one is necessary) and a catalyst section. A gas burner preheats the contaminated gases before they flow to the catalyst section. Drawings of two catalytic afterburner installations are shown in Figures 111 and 112. Arrangements for the recovery of heat from the afterburner gases are illustrated.

Frequently, the contaminated gases are delivered to the afterburner by the fan exhausting the process equipment. In one type of catalytic afterburner, the exhaust fan is located within the afterburner housing between the preheat burner and the catalyst bed. This fan also mixes the gases and distributes them evenly over the catalyst. Condensates do not occur in the fan since it operates above condensation temperature. Of course, the fan must be constructed of materials that can withstand the maximum temperature of the gases being handled.

The interior chamber of the afterburner may be constructed of 11- to 16-gage black iron, heat-resisting steel, stainless steel, or refractory materials. Heat-resisting steel should be used for operating temperatures between 750° and 1,100°F; stainless steel is recommended for operating temperatures exceeding 1,100°F. Refractory materials are recommended for temperatures exceeding 1,300°F. A thickness of 4 to 6 inches of similar thermal insulation is required unless refractory materials are used. The exterior sheet is usually fabricated from 16- to 20-gage mild steel. The framework is usually fabricated from standard structural steel. Gas velocities through the chamber of about 20 fps have been found satisfactory.

The contaminated gases are preheated to the reaction temperature by a gas burner before passing through the catalyst. When the preheat burner is on the discharge side of a fan, a premix gas burner is normally used because of the positive pressure in the afterburner chamber. When the fan is between the preheat burner and the catalyst bed, an atmospheric burner may be used since a negative pressure exists in the preheat section of the afterburner chamber. Sizing the preheat burner seems advisable to increase the temperature of the contaminated gases to the required catalyst discharge gas temperature without regard to the heating value of the combustible materials contained in the contaminated gas stream, especially if considerable variation in concentration occurs. The concentration of combustibles from the process equipment is normally 25 percent of the lower explosive limit or less to meet the requirements of the National Board of Fire Underwriters.

Experience indicates that the preheat burner should have sufficient capacity to heat the contaminated gas stream to 950°F minimum to obtain adequate catalytic combustion of the compounds that are more difficult to burn.

The operating temperatures of catalytic afterburners are usually about 650° to 1,000°F. This is lower than that of most direct-fired

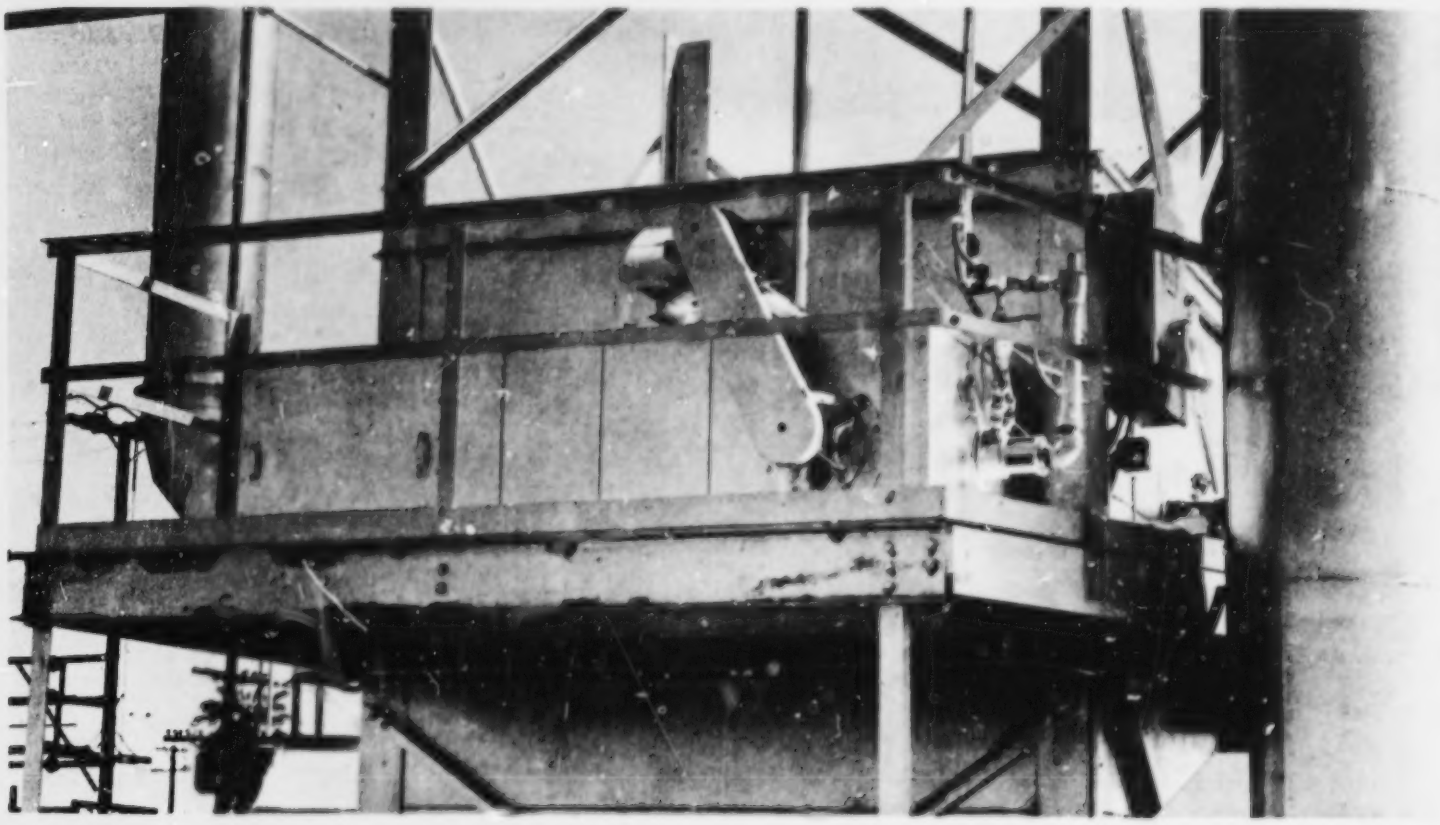


Figure 108. A catalytic afterburner used to control a foundry core baking oven (Catalytic Combustion Corporation, Detroit, Michigan).

afterburners, but feasible for air contaminants that are burned readily at these lower temperatures. Direct-fired afterburners are ordinarily installed to incinerate smoke and organic aerosols that are more difficult to burn.

An oxidizing catalyst is employed. Because of its high activity the catalyst is usually platinum with alloying metals. Other possible catalysts include copper chromite and the oxides of copper, chromium, manganese, nickel, and cobalt (Krenz et al., 1957). The catalyst has a very porous, highly adsorptive surface. It is deposited upon nickel alloy ribbon and formed into filter-like mats (type A) or deposited upon small, thin, ceramic rods for the fabrication of small blocks or bricks (type B). The two types of catalyst elements are shown in Figure 113.

Catalytic afterburners possess an inherent maintenance factor not present in direct-fired afterburners, namely, that usage of the catalyst produces a gradual loss of activity through fouling and erosion of the catalyst surface. Occasional cleaning and eventual replacement of the catalyst are, therefore, required.

Modulating controls on the burner regulated by the catalyst discharge gas temperature are usually used. This allows the fuel gas input to the preheat burner to be reduced as the rate of heat released in the catalyst bed increases as a result of larger concentrations of combustible vapors. The sensing instrument commonly used is a type employing a fluid-filled bulb for detecting gas temperature with capillary and bellows. Movement of the bellows is amplified and transmitted to the preheat burner gas valve and combustion air blower blast gate. Electronic instruments are used less frequently because of considerably greater cost.

When operating conditions do not vary greatly, an improved means of ensuring maximum afterburner efficiency seems to be the firing of the preheat burner at a fixed input capable of heating the contaminated gases to the temperature required for complete oxidation at the maximum rate of influx. Installation of a high-temperature-limiting control on the downstream side of the catalyst may be necessary to prevent overheating of the afterburner.

Operation

The contaminated gases are delivered to the afterburner by the exhaust fan. The gases pass into the preheat zone where they are heated to the temperature required to support

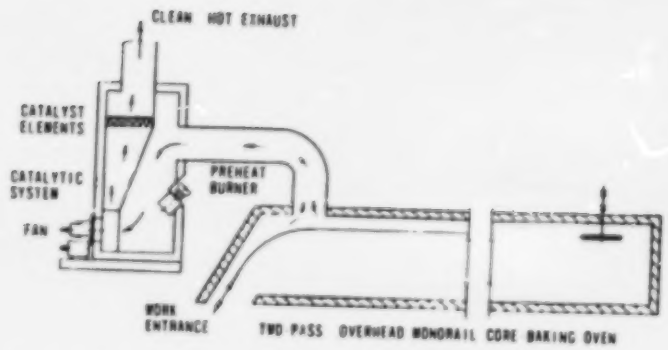


Figure 109. A catalytic afterburner venting a foundry core baking oven (Catalytic Combustion Corporation, Detroit, Michigan).

catalytic combustion. This temperature varies with the nature and composition of the contaminants to be burned, generally being about 650° to 1,000°F. Some burning of contaminants usually occurs in the preheating zone. The preheated gases then flow through the catalyst bed where the remaining combustible contaminants are burned by catalysis.

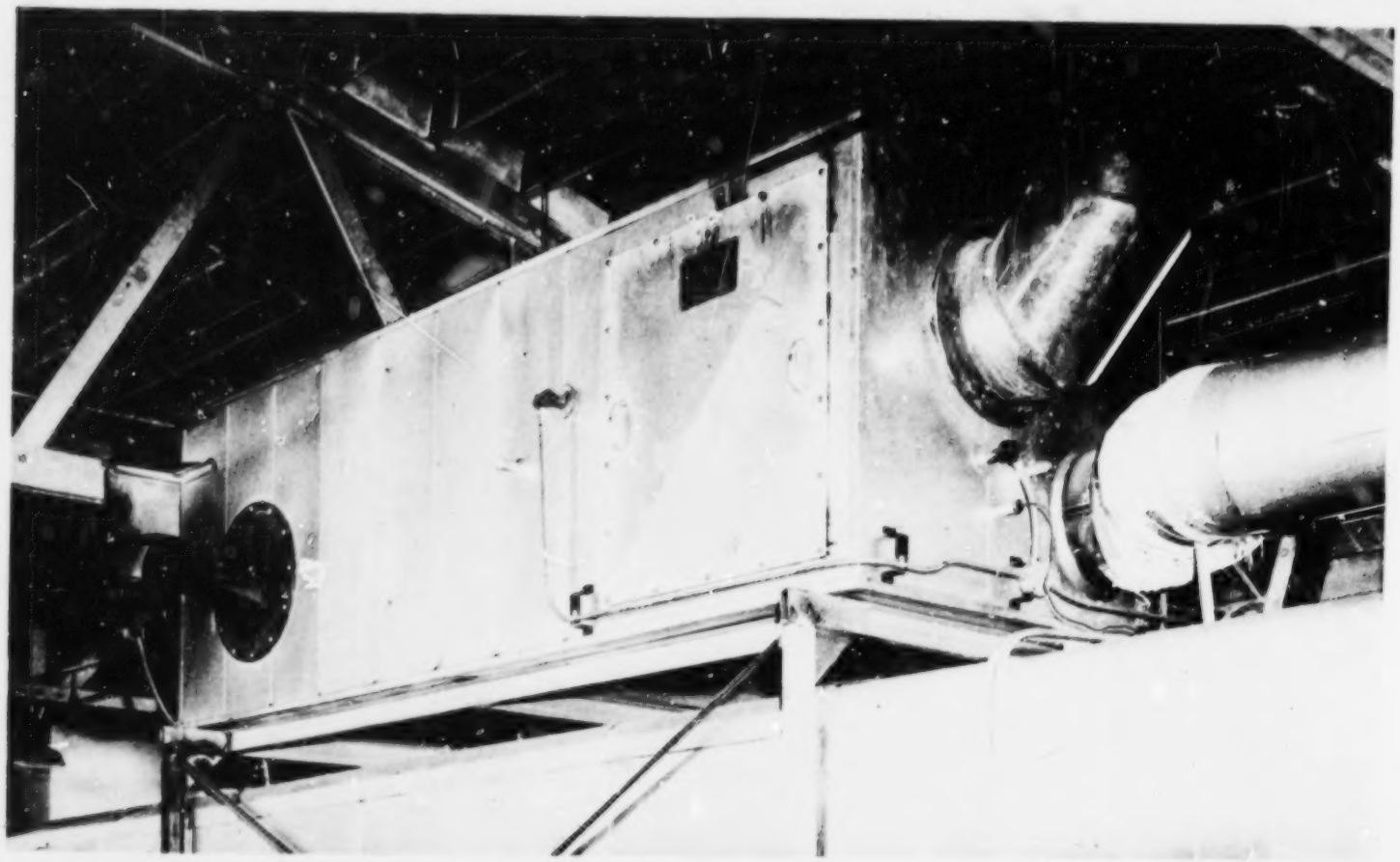
The combustible materials may be present in any concentration below the flammability limit. The factors influencing their combustion are temperature, oxygen concentration, contact with the catalyst surface, and nature of materials to be burned. Since the combustion reaction is exothermic, an increase in catalyst temperature is produced. The greater the concentration of combustibles in the entering gases, the greater the heat release rate and the higher the catalyst temperature. When this effect is appreciable, the initial preheat temperature of the entering gases can be reduced after the combustion reaction is established. This may be accomplished by providing modulating control of the preheat burner input actuated by an element sensing afterburner discharge gas temperature. In this way essentially constant afterburner discharge gas temperature and catalyst temperature can be maintained. Preheat fuel consumption is then theoretically inversely proportional to the concentration of combustibles in the entering gases.

The catalytic reaction depends upon the diffusion of combustible vapor molecules to the porous catalyst surface where they are adsorbed. Oxygen in a highly active state is also adsorbed on this surface. The combustion reaction takes place, and the combustion products are desorbed. Low-molecular-weight materials may react more readily than those of high molecular weight because of higher diffusion rates. The stability of the molecule, however, must also be considered. Methane is an example of a stable low-molecular-weight compound requiring a high temperature for catalytic combustion, about 760°F (Suter, 1955), whereas hydrogen may be catalytically burned at a temperature of about 500°F (Oxycat Technical Manual, 1956). The complete oxidation of more stable compounds requires higher temperatures and greater catalyst surface than those for less stable compounds. Entrained particles and liquid droplets are not likely to contact the catalyst surface to any appreciable degree because of their greater mass and lack of diffusional movement (Suter, 1955).

A direct relationship may exist between the auto-ignition temperature of an organic vapor and the temperature at which catalytic oxidation will occur. In other words, the higher the auto-ignition temperature of a compound, the higher the expected temperature required for catalytic oxidation.

Flow through the catalyst bed should be turbulent to promote contact of the contaminants with the catalyst surface. For adequate incineration, the combustible substances must be in the vapor phase or must be capable of being vaporized at a reasonably low temperature in the preheat zone. Reaction products must be sufficiently volatile for complete desorption from the catalyst surface (Suter, 1955).

Substances that poison the catalyst must not be present. Some of these are the vapors of metals such as mercury, arsenic, zinc, and lead. Substances that form solid oxides must also be



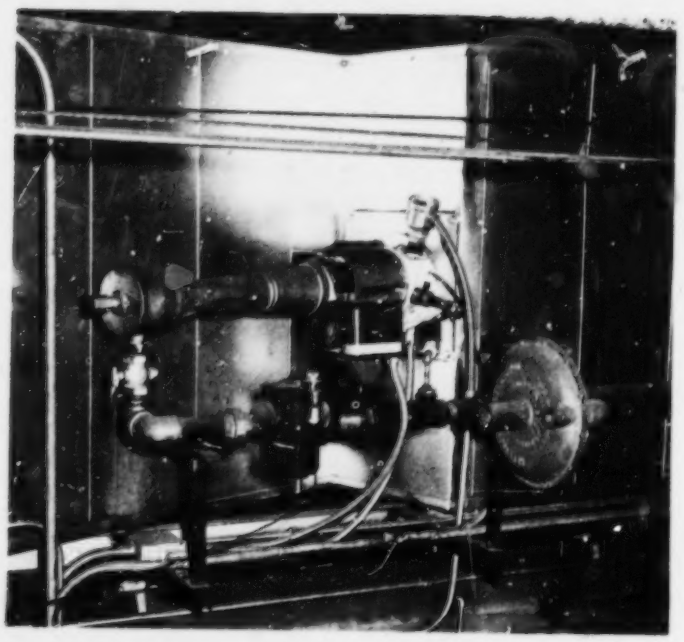


Figure 110. A catalytic afterburner controlling emissions from a sheet metal-coating baking oven (Advance Metal Lithographing, Inc., El Monte, Calif.).

avoided since they coat the catalyst surface and render it inactive. Some types of halogenated hydrocarbons are also harmful to the catalyst.

Finally, the burned gases are discharged through a stack to the atmosphere, to a process that may use the sensible heat of the exhaust gases, such as a bake oven or dryoff oven, or they may be passed through an exchanger for heating the gases entering the afterburner, which thereby reduces the amount of fuel required by the preheat burners.

At least the theoretical quantity of oxygen required for complete oxidation of the combustible gases must be contained in the influent gases. The efficiency of the catalyst is, however, normally greater when excess oxygen is present.

Complete mixing of the contaminated gases with the preheat burner combustion gases is required for optimum performance of the afterburner. This may be accomplished by baffles, elbows, or a centrifugal fan. Moreover, the flow of gases through the catalyst bed must be uniform. This may be accomplished by means of splitting vanes or a perforated baffle plate located upstream from the bed.

A maximum operating temperature of 1,800°F is indicated for one make of catalytic afterburner. This limit is apparently imposed by the materials used in construction and by the catalyst. Some solvent emissions from coating and lithograph bake ovens are usually found adequately controlled at catalyst discharge temperatures of 950° to 1,000°F. For a properly designed catalytic afterburner, an overall efficiency of 80 percent in the reduction of particulate matter may be expected. For solvents known to burn at relatively low temperatures, the con-

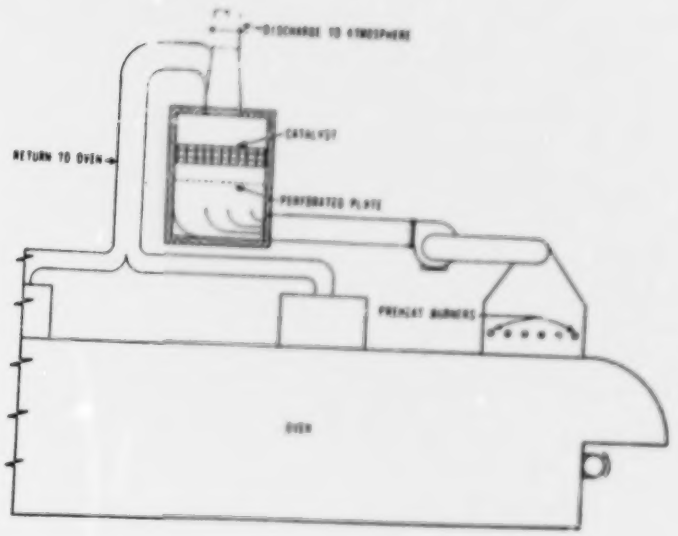


Figure 111. Typical catalytic afterburner utilizing direct heat recovery.

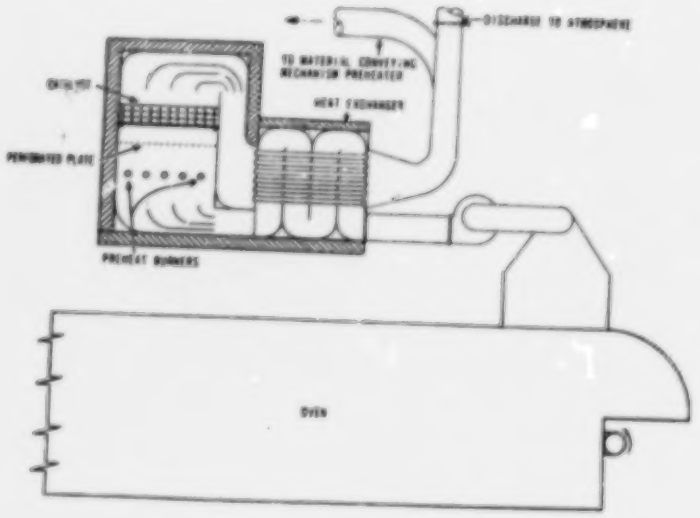


Figure 112. Typical catalytic afterburner utilizing indirect heat recovery.

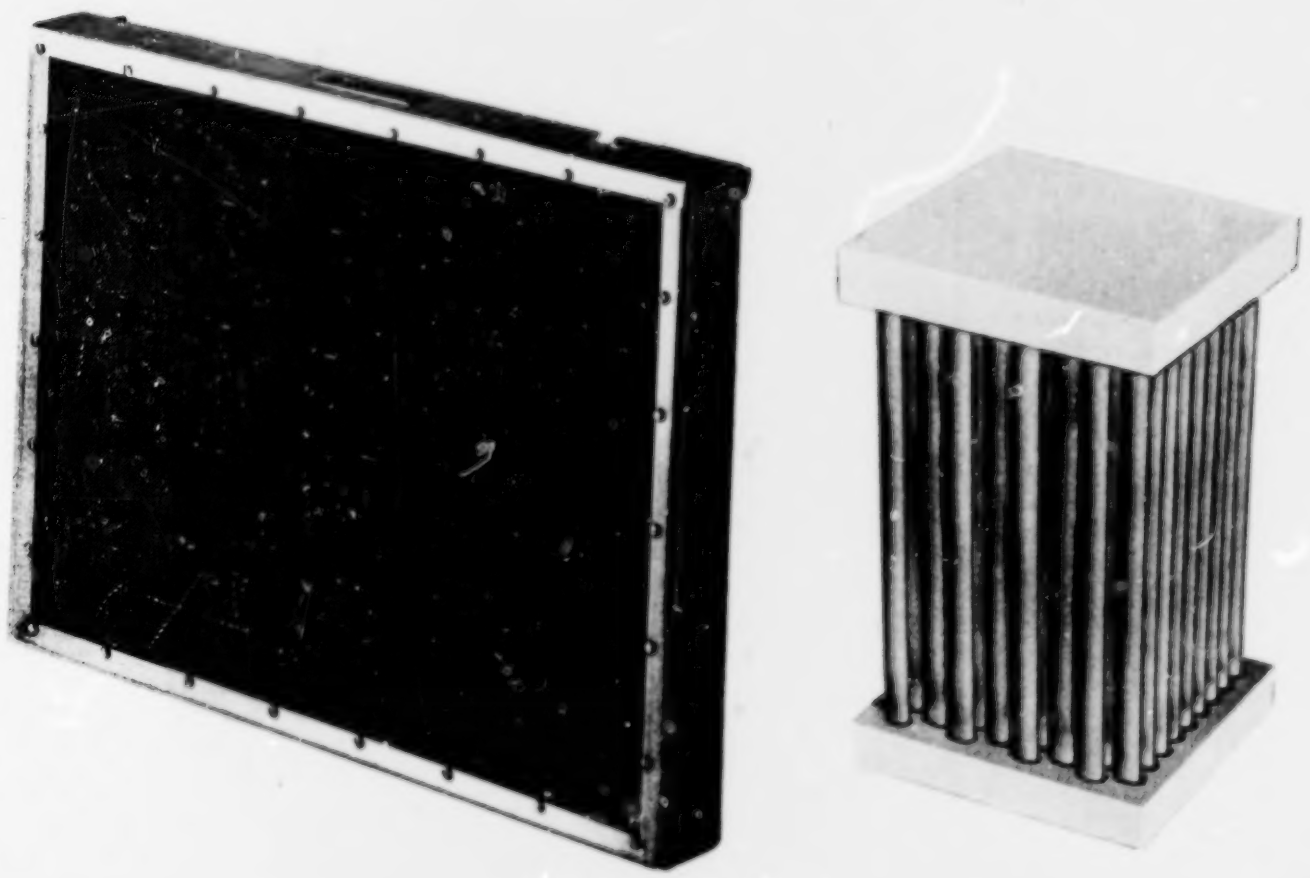


Figure 113. Afterburner catalyst elements: Left, metallic-ribbon-type catalyst element, type A (Catalytic Combustion Corporation, Detroit, Mich.); right, porcelain-rod-type catalyst element, type B (Oxy-Catalyst, Inc., Berwyn, Pa.).

centration of particulate matter in the stack gas has been reduced to as low as 0.01 grain per scf.

Table 52 summarizes the operating conditions and shows the coating applied for several coating ovens during tests of their catalytic afterburners. The temperature range of the catalyst is the range over which a series of tests was made, the catalyst's discharge temperature being held constant for each test. The catalyst's superficial gas velocities were constant within ± 15 percent for all runs. Figure 114 shows hydrocarbon combustion efficiencies as determined by tests of six different installations, all similar in operation though differing in type of coating, and type and quantity of solvents, as given in Table 52.

A hypothetical overall efficiency has been calculated to show total air pollution reduction. This is the total reduction of aldehydes as formaldehyde, hydrocarbons as hexane, and particulate matter. Figure 115 shows the resulting curves over a range of 800° to 1,200°F for coatings Numbers 1, 3, and 5 of Table 52.

In some instances the eye irritating characteristic of gases discharged from equipment has been more noticeable after a catalytic afterburner was installed. This is thought to be due to the partial oxidation of organic substances to aldehydes and organic acids. This condition has been more apparent at operating temperatures below 900°F. Little eye irritation or odor is usually experienced at operating temperatures above 900°F.

Efficiency

The efficiency of a catalytic afterburner depends upon several variables, namely, contact of the gases with the catalyst, uniform flow of the gases through the catalyst bed, operating temperature, catalyst surface area, nature of materials being burned, and oxygen concentration. Catalyst manufacturers specify a maximum scfm per catalyst unit.

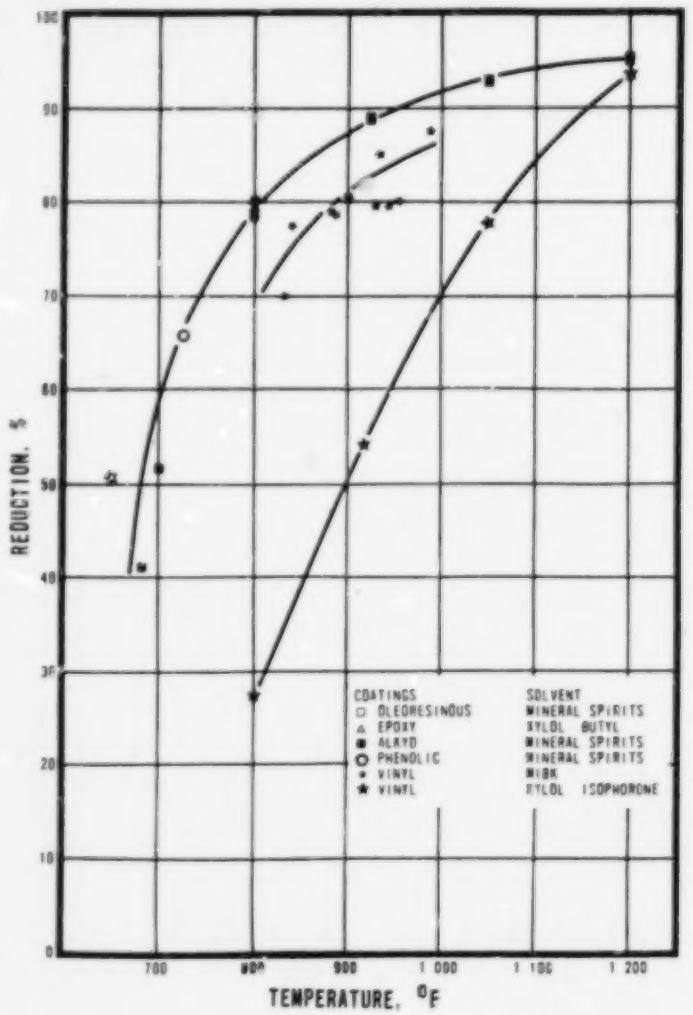


Figure 114. Hydrocarbon combustion efficiency of catalytic afterburners (Krenz et al., 1957).

Table 52. COATING OVEN OPERATING CONDITIONS DURING TESTS
(Krenz, Adrian, and Ingels, 1957)

Coating No.	Type	Quantity of coating, gal/hr	Solvent	Quantity of solvent, lb/hr	Oven temp range, °F Avg	Max	Catalyst temp range, °F
1	Vinyl	19	Xylol, isophorone	120	350	370	800 to 1,200
2	Vinyl	43	Methyl isobutyl ketone	271	340	370	800 to 1,000
3	Epoxy	18.6	Xylol, butyl cellosolve	86	350	390	800 to 1,200
4	Phenolic	18.5	Aromatic mineral spirits	88	414	430	730
5	Oleoresinous	17.5	Aromatic mineral spirits	77	425	475	800 to 1,200
6	Alkyd	8	Aromatic mineral spirits	30	290	300	700 to 900

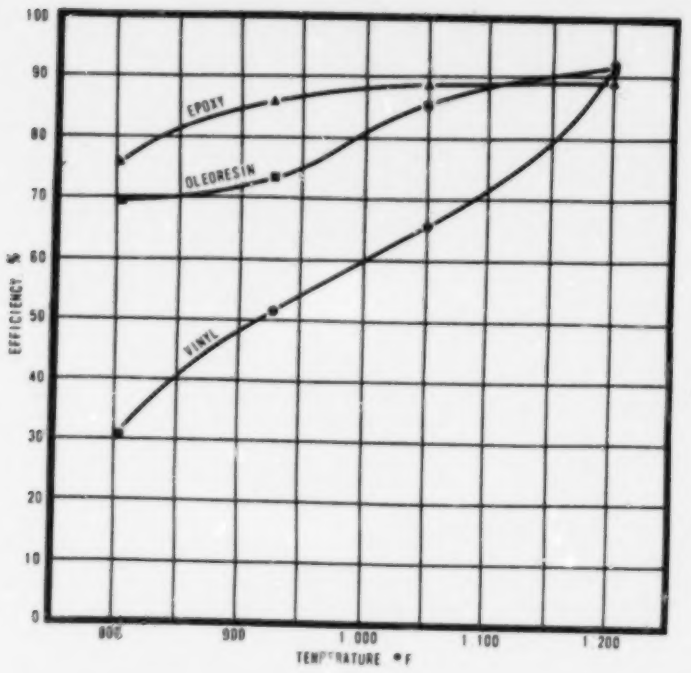


Figure 115. Efficiency of a catalytic afterburner as a function of catalyst temperature (Krenz, Adrian, and Ingels, 1957).

The efficiency at various temperatures of several catalytic afterburners serving paint bake ovens processing a variety of coating materials is shown graphically in Figure 115.

Design calculations

The following example illustrates some of the factors that must be considered in the design of a catalytic afterburner.

Example 22

Given:

A catalytic afterburner is to be installed to incinerate the air contaminants discharged from a direct-fired process oven. Visible emissions are to be eliminated and odors are to be reduced. A maximum gas discharge rate of 3,000 scfm at 200°F has been determined. Assume the effluent gases have the same properties as air. (See example for direct-fired afterburner for explanation.)

Problem:

Determine the design features of a catalytic afterburner to incinerate the contaminants in the exhaust gases.

Solution:

1. Mass flow rate of contaminated gases:

$$\frac{(3,000 \text{ cfm})(60 \text{ min/hr})}{13.1 \text{ ft}^3 \text{ air/lb air}} = 13,740 \text{ lb/hr}$$

2. Heat required to increase the temperature of the gases from 200° to 950°F:

Catalytic afterburner operating temperatures of approximately 950°F have been found sufficient to control emissions from most process ovens.

Enthalpy of gas at 950°F = 222.8 Btu/lb (see Table D3, Appendix D)

Enthalpy of gas at 200°F = 33.6 Btu/lb

Δh = 189.2 Btu/lb

(13,740)(189.2) = 2,600,000 Btu/hour

3. Heat losses from afterburner due to radiation, convection, and conduction:

Assume 10 percent of item 2. This appears to be a reasonable estimate based on the usual afterburner construction and operating temperatures.

(2,600,000)(0.10) = 260,000 Btu/hour

4. Total heat required by afterburner:

2,600,000 + 260,000 = 2,860,000 Btu/hour

5. Required natural gas volume capacity of burner:

(See example for direct-fired afterburner for explanation.)

Gross heating value of natural gas taken at 1,100 Btu/ft^3.

Net heat available at 950°F from the burning of 1 ft^3 of natural gas with theoretical air is 785.2 Btu/ft^3. (See Table D7, Appendix 7.)

$$\frac{2,860,000}{785.2} = 3,640 \text{ ft}^3\text{/hour}$$

6. Maximum gross heat release rate required of gas burner:

(3,640)(1,100) = 4,000,000 Btu/hour

7. Furnace combustion volume required for gas burner:

Heat release rates in the range of 50,000 Btu/hr-ft^3 have been used for some catalytic afterburner installations. This appears to be a reasonable value for design purposes.

$$\frac{4,000,000}{50,000} = 80 \text{ ft}^3$$

Additional volume will be required owing to displacement of catalyst elements.

8. Volume rate of gas burner combustion products at 950°F:

With theoretical air, 1 ft^3 of natural gas yields 11.45 ft^3 of products of combustion (see Table D7, Appendix D).

$$\frac{(3,640)(11.45)(950 + 460)}{(60 + 460)(3,600)} = 31.4 \text{ ft}^3/\text{sec}$$

9. Volume rate of contaminated gases at 950°F:

$$\frac{(3,000)(950 + 460)}{(60)(60 + 460)} = 135.6 \text{ ft}^3/\text{sec}$$

10. Total volume rate of gases in afterburner at 950°F:

$$31.4 + 135.6 = 167.0 \text{ ft}^3/\text{sec}$$

11. Number of catalyst elements required:

The type A catalyst element is 19 x 24 x 3-3/4 in. Experience has shown that a superficial gas velocity through the catalyst bed of about 10 fps is satisfactory.

$$\frac{(167.0)(144)}{(10)(19)(24)} = 5.27, \therefore \text{ Use 5 type A catalyst elements}$$

The type B catalyst element is 3 x 3-1/8 x 5-1/2 in. and is rated by the manufacturer at 5 to 15 scfm per element, depending upon the application. Use 10 scfm per element.

$$\frac{3,000}{10} = 300, \therefore \text{ Use 300 type B catalyst elements}$$

Results of several tests of catalytic afterburners are given in Table 53. The process equipment and the afterburners in each of these tests are briefly discussed below.

Test C-410

Test C-410 was conducted on a catalytic afterburner serving a conveyorized, gas-fired paint bake oven. Sheets of tin plate were roller coated with a vinyl coating and baked at 350°F. The solvent-laden gases were vented to the preheat zone of the catalytic afterburner where they were heated to 950°F by an atmospheric-type gas burner. A portion of the solvent vapors was burned by the preheat burner. From the preheat zone, the gases were drawn into an exhaust fan located within the afterburner housing and discharged through a bank of four catalyst elements that use a metallic ribbon catalyst support. A considerable portion of the remaining solvent vapors was burned.

Table 53. STACK ANALYSES OF EMISSIONS FROM CATALYTIC AFTERBURNERS

Report series No.	C-410	C-374	C-374	C-374	C-374
Basic equipment	Paint bake oven	Paint bake oven	Paint bake oven	Paint bake oven	Paint bake oven
Burner type	Atmospheric	Premix	Premix	Premix	Premix
Catalyst support	Metallic ribbon	Porcelain rod	Porcelain rod	Porcelain rod	Porcelain rod
Afterburner combustion chamber temp, °F	1,000	800	925	1,050	1,200
Inlet gas volume, scfm	--	5,800	5,900	5,400	5,400
Outlet gas volume, scfm	2,300	6,100	6,200	5,800	5,900
Particulate matter, lb/hr, inlet	6.7	4.4	9.0	9.9	7.7
Particulate matter, lb/hr, outlet	1.4	2.6	4.5	3.6	2.2
Control efficiency, %	79	41	50	64	71
Aldehydes, lb/hr, inlet	0.07	0.3	0.3	0.3	0.4
Aldehydes, lb/hr, outlet	0.31	0.2	0.4	0.2	0.5

It seems significant that the amount of aldehydes discharged from the afterburner is approximately four times the amount entering. Large amounts of aldehydes are typical of incomplete combustion.

Test C-374

A series of tests was conducted on a second catalytic afterburner serving a conveyorized gas-fired paint bake oven. The afterburner is a type wherein the catalyst elements are small blocks of thin porcelain rods on which the catalyst is deposited. Sheets of tin plate were roller coated with a vinyl coating and then conveyed through the oven and baked at about 320°F. An exhaust fan discharged the gases and solvent vapors to a heat exchanger where the contaminated gases were preheated before entering the afterburner. The gases were then further preheated by gas burners before entering the catalyst section. The sensible heat of the gases discharged from the afterburner was used to preheat the incoming contaminated gases in the heat exchanger.

Test results show that an appreciable fraction of the particulate matter was burned by the preheat burners, an additional fraction being burned in the catalyst section. Moreover, the overall efficiency of the afterburner in the burning of particulate matter increased noticeably with increased afterburner temperature. There is, however, no significant change in the concentration of aldehydes in the inlet and outlet gases.

Installation Costs

A survey of installation costs of catalytic afterburners reveals a general range from $5.00 to $10.00 per scfm contaminated gas.

BOILERS USED AS AFTERBURNERS

Fireboxes of boilers and fired heaters can be used, under proper conditions, as afterburners to incinerate combustible air contaminants. This use is unique in that a basic source of air contaminants, a boiler, is used to control pollutants from another source. Boiler firebox conditions approximate those of a well-designed afterburner, provided there are adequate temperature, retention time, turbulence, and flame. Oxidizable contaminants, including smoke and organic vapors and gases, can be converted essentially to carbon dioxide and water in boiler fireboxes.

The discussion of this section is limited to the control of low-calorific-value gases and vapors with common types of steam and hot water boilers and heaters. When appreciable heat is contained in the contaminated gases, the firebox is usually of special design to take advantage of the heat potential. These latter units, commonly known as waste heat boilers, are discussed in Chapter 9.

Completely satisfactory adaptations of boilers for use as afterburners are not common. All aspects of operation should be thoroughly evaluated before this method of air pollution control is used. The primary function of a boiler is to supply steam or hot water, and whenever its use as a control device conflicts with this function, one or both of its purposes will suffer. Some advantages and disadvantages of boilers used as afterburners are shown in Table 54.

CONDITIONS FOR USE

The determination to use a boiler as an afterburner demands that the following conditions exist:

1. The air contaminants to be controlled must be almost wholly combustible since a boiler firebox cannot be expected to control noncombustible pollutants. Inorganic dusts and fumes deposit on heat transfer surfaces and foul them with resulting losses in boiler efficiency and steam-generating capacity.

2. The volumes of contaminated gases must not be excessive or they will reduce thermal efficiencies in much the same way as excess combustion air does. The additional volume of products of combustion will also cause higher pressure drops through the system, in some cases exceeding the draft provided by existing boiler auxiliaries.

3. The oxygen content of the contaminated gases when used as combustion air must be similar to that of air to ensure adequate combustion. Incomplete combustion can form tars or resins that will deposit on heat transfer surfaces and result in reduction of boiler efficiency. When these contaminants exceed air pollution control standards for gas- or oil-fired boilers, tube fouling will already have become a major maintenance problem.

4. An adequate flame must be maintained continuously in the boiler firebox. High-low or modulating burner controls are satisfactory provided that the minimum firing rate is sufficient to incinerate the maximum volume of effluent that can be expected in

Table 54. ADVANTAGES AND DISADVANTAGES OF USING A BOILER AS AN AFTERBURNER RATHER THAN A CONVENTIONAL DIRECT-FIRED AFTERBURNER

Advantages	Disadvantages
1. Large capital expenditure not required.	1. If air contaminant volumes are relatively large, boiler fuel cost may be excessive.
2. Boiler serves dual purpose as source of process steam and as an air pollution control device.	2. High maintenance cost may be required because of burner and boiler tube fouling.
3. Auxiliary fuel not required for operation of air pollution control device.	3. Boiler must be fired at an adequate rate at all times when effluent is vented to the firebox, regardless of steam requirements.
4. Operating and maintenance cost limited to one piece of equipment.	4. Normally, two or more boilers must be used, one as standby during shutdowns.
5. Fuel saving, if effluent has some calorific value (rare instances).	5. Pressure drop through boiler may be excessive if large volume of effluent introduced into boiler causes back pressure on exhaust system.

the boiler firebox. Obviously a burner equipped with on-off controls would not be feasible.

Boilers used as afterburners have successfully controlled visible emissions from meat smokehouses and also obnoxious odors from rendering cookers and from oil refinery processes involving cresylic and naphthenic acids, hydrogen sulfide, mercaptans, sour water strippers, ammonia compounds, regeneration air from doctor treating plants, oil mists and vapors from process columns, and so forth.

MANNER OF VENTING CONTAMINATED GASES

Like other types of controls, these units require a properly designed exhaust system to convey air pollutants effectively from the point of origin to the boiler firebox.

Contaminated gases may be introduced into the boiler firebox in two ways: (1) Through the burner, serving as combustion air, or (2) downstream of the burner, serving as secondary air.

Figures 116 and 117 show poor and good installations wherein the contaminated gases are introduced through the burner. The oxygen content of these gases must be nearly equivalent to that of air to ensure good combustion. Excessive volumes of nonoxidizing gases such as CO_2, H_2O, and N_2 can cause undesirable results ranging from flame popping to complete outage of the burner. Introducing contaminated gases through the burner should promote good flame contact, turburlence, temperature, and retention time.

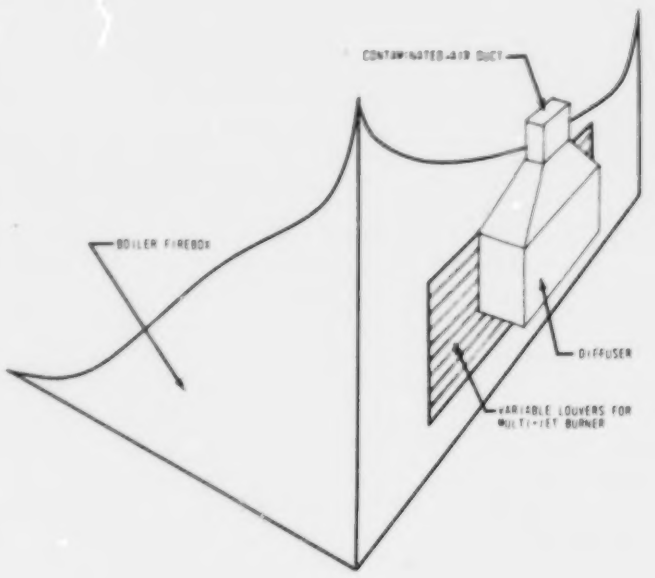


Figure 116. Poor method of introducing contaminated air from diffuser to boiler firebox through the burner air register. Diffuser restricts combustion air to burner. Moreover, louver may partially close restricting flow of contaminated air into boiler firebox.

Since the polluted gas stream furnishes a part of the combustion air for the burner, less additional air is required from the combustion air system. Burner maintenance costs, however, are higher. Contaminated gases should not be introduced through the burner if a high moisture content or corrosive gases and vapors are present. In these cases, the gases should be introduced into the boiler downstream of the burner.

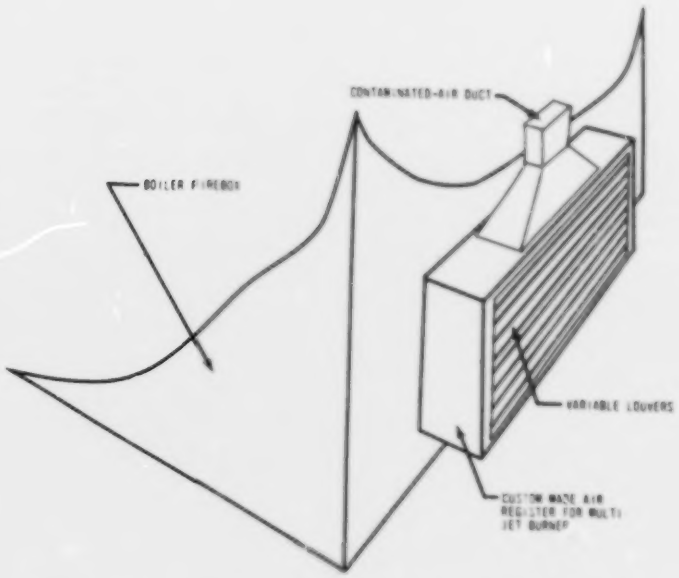


Figure 117. Good method of introducing contaminated air to boiler firebox through a custom-made air register. There is good flame contact. Contaminated air enters firebox through burner. Note: type of burner is critical; contaminated air is portion of combustion air; not applicable where contaminated gases are corrosive.

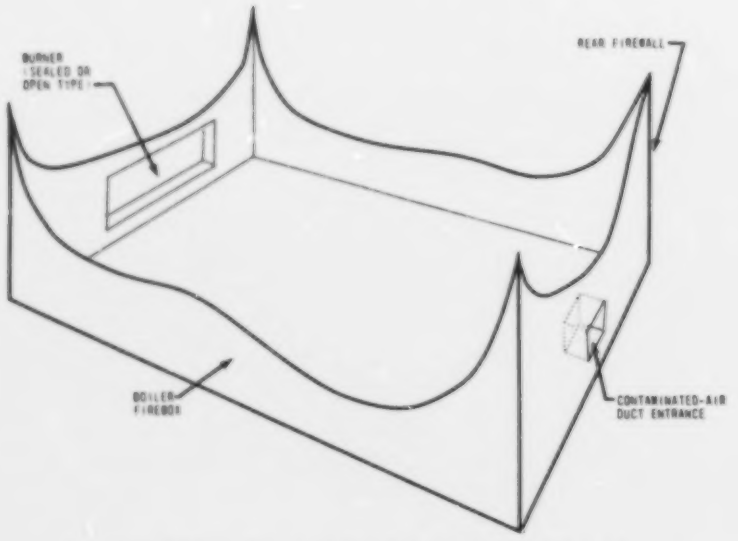


Figure 118. Poor method showing entry of contaminated air near boiler firebox rear firewall. Flame contact is poor.

Figures 118, 119, and 120 show both desirable and undesirable methods of introducing contaminated gases downstream of the burner. Gases must be carefully directed into the boiler firebox to ensure adequate flame contact. An exhaust fan or a steam ejector is used to convey the effluent through an exhaust system from the source into the boiler firebox. Sometimes, a flame arrestor is installed to prevent flashback. When gases of high moisture content must be incinerated, condensers are installed upstream of the boiler.

A reduction in boiler efficiency should be expected when gases are introduced directly into the boiler firebox. In addition, incineration may not be complete, and partially oxidized organics may be present in the products of combustion. As a result, these particulates deposit on boiler tubes and reduce heat transfer. Because of these disadvantages, this latter method should be used only when the contaminated gases cannot be introduced directly through the burner.

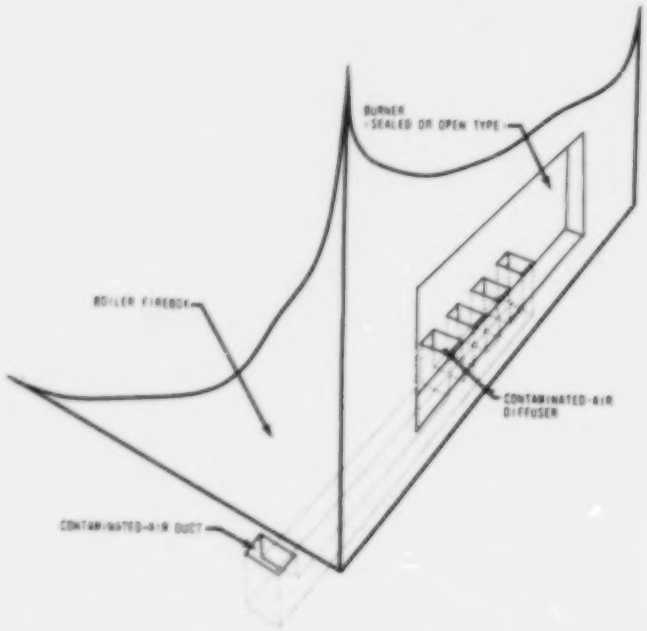


Figure 119. Boiler firebox showing entry of contaminated air through a diffuser in the floor near the burner. The possibility for flame contact is good. Note: Type of burner is not critical; contaminated air is secondary air for boiler; applicable where contaminated gases are corrosive.

ADAPTABLE TYPES OF EQUIPMENT

Boilers and Fired Heaters

Water-tube, locomotive, or HRT boilers and fired heaters are the units most frequently used as afterburners. Burners used with these units are usually adaptable to incineration, and the fireboxes are usually accessible. Thus, the contaminated gases may be properly introduced either through the burner or through the floor or sides of the fireboxes.

Some types of boilers do not provide these features. For example, polluted gases usually

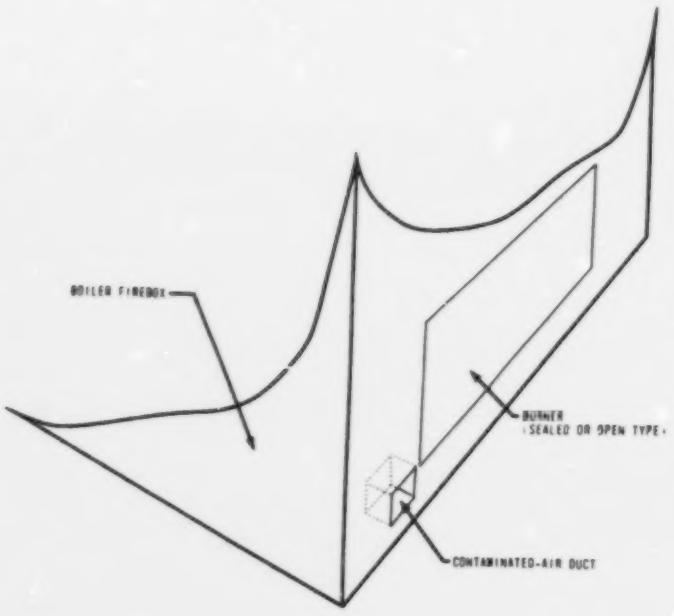


Figure 120. Boiler firebox showing entry of contaminated air through a duct at front of boiler. Flame contact and mixing are poor.

cannot be introduced into the firing tube of a Scotch marine boiler unless they are introduced with the combustion air. Admitting contaminated gases through the integral blower of a forced-draft burner is normally not feasible.

Burners

Burner selection is greatly influenced by boiler or heater firebox design, the method of introducing polluted gases, and the characteristics of the pollutants themselves.

Where gases are introduced as excess air through the sides or floor of the firebox, any standard gas or oil burner may be used. The gases must, however, be introduced near the burner end of the firebox to ensure adequate incineration.

Where contaminated gases are used as combustion air, natural or induced draft is essential. Multijet natural-gas burners and steam, pressure, or air-atomizing oil burners are most adaptable. The burner must be thoroughly maintained according to the character of contaminants to be incinerated. Forced draft burners are not recommended because of the probability of corroding and fouling burner controls and blowers.

SAFETY

As with any afterburner or flare used to incinerate combustible gases, care must be taken to prevent flashbacks and firebox explosions. This problem is most acute when the contaminated gas stream contains explosive hydrocarbon concentrations, for example, a refinery flare. In these instances, suitable flame arrestors are required. Where continuing explosive concentrations are likely, a control device other than a boiler-afterburner is recommended. Flaring or intermediate gas storage for use as fuel might well be a more practical approach than on-line incineration.

Contaminants in most exhaust gas streams are normally well below explosive concentrations. In a few processes, however, combustible gas concentrations can accumulate during shutdowns with resultant explosion hazards on lightoff of the boiler. For instance, a batch of raw or partially cooked animal matter might be left overnight in a rendering cooker ducted to a boiler-incinerator. This could generate enough methane, hydrogen sulfide, and other organics to produce an explosive mixture in the ductwork leading to the boiler. If, subsequently, the burner were ignited without first purging the line, an explosion could occur. To avoid a rare possibility such as this, both the boiler firebox and the ductwork should be purged before igniting the burner.

Some fire hazard is created by the accumulation of organic material in ductwork. Lines such as these must usually be washed periodically. The degree of organic accumulation can sometimes be reduced by frequent steam purging or by heating the ductwork to prevent condensation.

DESIGN PROCEDURE

When evaluating a control system wherein a boiler is to be used as an afterburner, one should:

1. Determine the maximum volume, temperature, and characteristics of the polluted gases to be vented to the boiler firebox;
2. ascertain that the exhaust system from the source of the pollutant to the boiler firebox is properly designed;
3. determine the manner in which the pollutants are to be introduced into the boiler firebox;
4. calculate whether the boiler and burners are of sufficient size and design to handle the contaminated gases;
5. calculate the minimum firing rate at which the boiler must be operated to ensure adequate incineration;

6. provide that the firing rate does not fall below the minimum rate determined in item 5.

The following example shows some of the factors that must be considered in determining the feasibility of using a boiler to incinerate exhaust gases from four meat processing smokehouses.

Example 23

Given: Boiler data

Boiler, 150 hp, HRT type, multijet burner, gas fired only--minimum instantaneous firing rate, 38.2 cfm.

Automatic modulating controls, stack size, 30-in. diameter x 40 ft high.

Assumptions:

Boiler operates at 80% efficiency, stack temperature = 500°F, 20% excess air to burner.

Effluent data:

Maximum volume of effluent = 1,000 scfm, (76.4 lb/min) with smokehouse stacks dampered. Minimum temperature of effluent = 100°F.

Assumptions:

Effluent gases have the same properties as air. Exhaust system has been designed to convey effluent gases properly from smokehouses to boiler firebox. Effluent to enter boiler firebox as secondary air through diffuser in floor, near burner end. Minimum incineration temperature to be 1,200°F.

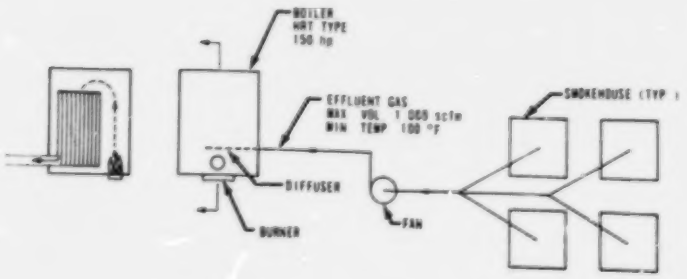


Figure 121. Sketch of proposed system.

Problem:

Determine whether use of a 150-hp HRT-type boiler as an afterburner is feasible.

Solution:

1. Btu input required to fire the 150-hp boiler at rating:

   1 boiler hp = 33,475 Btu/hr

   $$\frac{(150 \text{ hp})(33,475 \text{ Btu/hr})}{0.8 \text{ eff}} = 6,277,000 \text{ Btu/hr}$$

2. Natural gas flow required to fire boiler at rating:

   Gross heat standard of natural gas taken at 1,100 Btu/ft^3 at 60°F.

   $$\frac{6,277,000 \text{ Btu/hr}}{1,100 \text{ Btu/ft}^3} = 5,707 \text{ cfh or } 95.1 \text{ cfm}$$

3. Determine minimum firing rate for boiler:

   Instantaneous minimum firing rate for boiler determined by actual measurement = 38.2 cfm

   Therefore, minimum firing rate for boiler

   $$= \frac{38.2}{95.1}(100) = 40.2\% \text{ of rating}$$

4. Heat required from burner of boiler to raise temperature of smokehouse effluent from 100° to 1,200°F:

   Enthalpy of gas (1,200°F) = 287.2 Btu/lb (See Table D3 in Appendix D.)

   Enthalpy of gas (100°F) = 9.6 Btu/lb (See Table D3 in Appendix D.)

   (76.4 lb/min)(277.6 Btu/lb) = 21,209 Btu/min = 1,272,540

5. Natural gas flow required to supply 21,209 Btu/min:

   Heat available at 1,200°F from the burning of 1 ft^3 of natural gas with 20% excess air = 676.5 Btu/ft^3 (see Table D7 in Appendix D).

   $$\frac{21,209 \text{ Btu/min}}{676.5 \text{ Btu/ft}^3} = 31.4 \text{ cfm}$$

   Since only 31.4 cfm is required to raise temperature of smokehouse effluent from 100° to 1,200°F, minimum firing rate for boiler is adequate.

6. Volume of products of combustion from boiler firing at 150% rating with 20% excess air:

   One ft^3 of natural gas yields 13.473 ft^3 of products of combustion (see Table D7 in Appendix D).

Vol = (142.7 scfm)(13.473) = 1,922.7 scfm

7. Total volume vented from boiler:

Volume of effluent (secondary air) = 1,000 scfm
Volume of products of combustion = 1,922.7

Total volume vented = 1,000 + 1,922.7
= 2,922.7

8. Volume of gases vented at stack temperature of 500°F:

$$(2,922.7)\ \frac{(500° + 460°)}{(60° + 460°)} = 5,396 \text{ cfm}$$

9. Stack velocity:

$$\text{Vel} = \frac{5,396 \text{ cfm}}{(60 \text{ sec/min})(4.91 \text{ ft}^2)} = 18.32 \text{ ft/sec}$$

Note: Stack velocities not exceeding 30 ft/sec are satisfactory.

10. Heat required to raise temperature of effluent from 100° to 500°F (stack temperature):

Enthalpy of gas (500°F) = 106.7 Btu/lb
(See Table D3 in Appendix D.)

Enthalpy of gas (100°F) = 9.6 Btu/lb
(See Table D3 in Appendix D.)

Δh = 97.1 Btu/lb

(76.4 lb/min)(97.1 Btu/lb) = 7,418 Btu/min

11. Natural gas flow required to supply 7,418 Btu/min:

The net thermal energy per ft^3 natural gas above that required to bring the effluent to the stack temperature of 500°F = 878 Btu/ft^3 (see Table D7 in Appendix D).

$$\text{Vol gas} = \frac{7,418 \text{ Btu/min}}{878.0 \text{ Btu/ft}^3} = 8.45 \text{ cfm}$$

12. Incremental cost of natural gas (assume rate of $0.50 per 1,000 ft^3):

$$8.45 \frac{\text{ft}}{\text{min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{\$0.50}{1,000 \text{ ft}^3}$$

= $6.08/day

13. Cost of operating a direct gas-fired afterburner operating at same temperature (neglecting initial capital expenditure):

$$31.4 \frac{\text{ft}^3}{\text{min}} \times \frac{60 \text{ min}}{\text{hr}} \times \frac{24 \text{ hr}}{\text{day}} \times \frac{\$0.50}{1,000 \text{ ft}^3}$$

= $22.61/day

Problem note: Calculations indicate that use of this boiler as an afterburner is feasible. The boiler is fired at an adequate rate at all times, and excessive volumes of effluent are not vented to this boiler firebox. Costs, including initial capital expenditures, are nominal. Some additional cost might be necessary to provide more draft to offset increased pressure drops through the boiler.

TEST DATA

Tests have been conducted on several boilers used as afterburners. The majority of tests have been on boilers used to incinerate the effluent from meat smokehouses. One test, however, includes a boiler used to incinerate partially condensed vapors from rendering cookers.

Table 55 summarizes these test results and shows the apparent efficiencies of boilers in controlling combustion contaminants, organic acids, and aldehydes. Installations were such that tests could not be conducted with the boilers operating under identical conditions unless the contaminated gases were vented to the boiler fireboxes.

ADSORPTION EQUIPMENT

Adsorption is the name for the phenomenon in which molecules of a fluid contact and adhere to the surface of a solid. By this process, gases, liquids, or solids, even at very small concentrations, can be selectively captured or removed from airstreams with specific materials known as adsorbents. The material adsorbed is called the adsorbate.

A change in the composition of the fluid contacting the adsorbent results when one or more of the components are adsorbed by the adsorbent. The mechanism of this process is complex, and while adsorption can occur at all solid interfaces, it is usually small unless the solid is highly porous and possesses fine capillaries. The most important characteristics of solid adsorbents are their large surface-to-volume ratios and preferential affinity for individual components.

Table 55. TEST DATA ON BOILERS USED AS AFTERBURNERS

Equipment tested	426-hp boiler, water-tube type, gas fired[a]	Two 268-hp boilers, common stack water-tube type, gas fired[a]	200-hp boilers, water-tube type, gas fired[b]	Two 113-hp boilers, common stack locomotive type, gas fired[a]	150-hp boiler, HRT type, gas fired[c]	
Volume of gases, scfm						
Stack	8,700	10,300	4,700	3,800	3,400	3,600
Boiler inlet	1,600	2,930	2,400	320	470	750
Combustion contaminants, lb/hr						
Inlet	2.4	4.6	2.7	0.19	0.74	0.73
Outlet	0.45	0.53	1.6	0.16	0.52	0.71
Efficiency, %[d]	84	89	41	16	30	3
Organic acids, lb/hr						
Inlet	1.5	2.7	2.2	0.12	0.35	0.44
Outlet	0.56	0.64	1.4	0	0.14	0.38
Efficiency, %[d]	60	78	36	100	60	14
Aldehydes, lb/hr						
Inlet	0.22	0.39	0.39	0.03	0.012	0.03
Outlet	0.09	0.40	0.30	0	0.09	0.18
Efficiency, %[d]	59	0	23	100	0	0

[a]Meat smokehouse effluent was admitted into boiler firebox through the multijet burner.
[b]Meat smokehouse effluent was admitted into boiler firebox through diffuser located at front of firebox floor.
[c]Rendering cooker effluent was admitted into boiler firebox through diffuser located at rear of firebox floor. Two tests were run. The use of this boiler as an afterburner has been discontinued, primarily because the minimum firing rate of the boiler was insufficient to incinerate air contaminants.
[d]Efficiency shown is Apparent Efficiency. Boilers could not be tested unless air contaminant were vented to it.

Many theories have been advanced to explain the selective adsorption of certain vapors or gases, the exact mechanism being still disputed. In some cases, certainly, adsorption is due to chemical combination of the gas with the free valences of atoms on the surface of the solid in the monomolecular layer, as was proposed by Langmuir in 1916 (Glasstone, 1946). Other investigators hold that the adsorbents exert strong attractive forces, so that many adsorbed layers form. These layers are under pressure, partly because of layers on top and because of the attractive force of the surface of the adsorbent. In other cases, the evidence indicates that adsorption is due to liquefaction of the gas and its retention by capillary action in the exceedingly fine pores of the adsorbing solid. In many cases, the phenomena are probably superimposed. The adsorptive power of activated charcoal is due mainly to molecular capillary condensations while the adsorptive power of silica gel is due mainly to capillary condensation. Note, however, that the adsorptive power of any solid adsorbent may vary appreciably with the method of preparation as well as with the nature of the gas or vapor adsorbed (Walker et al., 1937).

In most processes involving adsorption, the operation involves three steps. First, the adsorbent is contacted with the fluid, and a separation by adsorption results. Second, the unadsorbed portion of the fluid is separated from the adsorbent. In the case of gases, this operation is completed on their passage through the adsorbent bed. Third, the adsorbate is removed from the adsorbent, which thereby regenerates the adsorbent. In some cases the adsorbent is regenerated without recovery of the adsorbate, as in the decolorizing of sugar solutions with bone char and the treatment of lubricating oils with Fuller's earth. In the treatment of domestic water with finely divided activated carbon, both the adsorbent and the adsorbate are separated from the fluid and discarded.

Regeneration, which involves raising the temperature of the adsorbent, may be performed by several methods, depending upon the adsorbate. In the examples cited previously, where the adsorbate has no economic value, the Fuller's earth and bone char are heated directly with hot gases. In the recovery of chlorine and sulfur dioxide from silica gel, the adsorbent is heated indirectly with a hot brine. In the recovery of solvents, low-pressure steam is used and the condensed vapors are separated from the water by decantation or distillation, or both.

Adsorption can be specific and can, therefore, be used to separate gases from gases, as in the elimination of toxic materials such as sulfur dioxide or chlorine; the removal of vaporized liquids from air, as in the capture of solvents in surface coating operations; the removal of colloids or suspended solids from solutions, as in the decolorizing, clarification, and purification of solutions; the removal of

ions from solutions, as in water softening; and the removal of dissolved gases in solution to control odors or tastes, as in water treatment.

TYPES OF ADSORBENTS

Solids possessing adsorptive properties exist in great variety. Some of these solids and their industrial uses are as follows:

Activated carbon	Solvent recovery, elimination of odors, purification of gases
Alumina	Drying of gases, air, and liquids
Bauxite	Treatment of petroleum fractions; drying of gases and liquids
Bone char	Decolorizing of sugar solutions
Decolorizing carbons	Decolorizing of oils, fats, and waxes; deodorizing of domestic water
Fuller's earth	Refining of lube oils and vegetable and animal oils, fats, and waxes
Magnesia	Treatment of gasoline and solvents; removal of metallic impurities from caustic solutions
Silica gel	Drying and purification of gases
Strontium sulfate	Removal of iron from caustic solutions

Activated carbon, silica gel, alumina, and bauxite are used for selectively adsorbing certain gaseous constituents from gas streams. Activated carbon adsorbs organic gases and vapors, even when water is present in the gas stream. Silica gel, in the absence of water vapor, adsorbs organic and inorganic gases; however, in the presence of water vapor, it adsorbs water vapor almost exclusively. Alumina and bauxite are used chiefly in dehydration. Bone char, decolorizing carbon, Fuller's earth, magnesia, and strontium sulfate are used mainly in removing impurities from solutions. Bone char and Fuller's earth are normally used as beds through which the solutions are allowed to percolate. Decolorizing carbon, magnesia, and strontium sulfate are added to the solution in finely divided form and intimately mixed. The amount added is sufficient only to effect the purification; the separation is made by settling or filtration.

USE OF ACTIVATED CARBON IN AIR POLLUTION CONTROL

Generally, the concentrations of the organic materials discharged to the atmosphere are relatively small and are usually governed by fire prevention regulations and the health hazard standards (Barry, 1960). The latter is usually smaller and in many cases is the governing concentration. Concentrations may vary from 50 to 3,000 ppm.

Activated carbon is the adsorbent most suitable for removing organic vapors. Carbon adsorbs substantially all the organic vapor from the air at ambient temperature regardless of variation in concentration and humidity conditions. Because the adsorbed compounds have practically no vapor pressure at ambient temperatures, the carbon system is particularly adapted to the efficient recovery of solvents present in air in small concentrations. This means the system can always be designed for operation without hazard because the vapor concentration is always below the flammable range.

Since activated carbon adsorbs all the usual low-boiling solvent vapors, it can be used to recover practically any single solvent or any combination of low-boiling solvents. Turk and Bownes (1951) state that the limitation for molecules capable of removal by physical adsorption is that they must be higher in molecular weight than the normal components of air. In general, removal of gaseous vapors by physical adsorption is practical for gases with molecular weight over 45. Probably the only solvent used with a molecular weight below 45 is methanol.

Saturation

Adsorption of a vapor by activated carbon apparently occurs in two stages. Initially, adsorption is rapid and complete, but a stage is reached in which the carbon continues to remove the material but at a decreasing rate. Eventually, the vapor concentration leaving the carbon equals that of the inlet. At this point the carbon is saturated, that is, it has adsorbed the maximum amount of vapor that it can adsorb at the specific temperature and pressure. This saturation value is different for each vapor and carbon. It is determined experimentally by passing dry air saturated with the gas or vapor, with temperature and pressure maintained constant, through a known amount of carbon until the carbon ceases to increase in weight. Under these conditions, the carbon is saturated with the adsorbate.

Retentivity

The retentive capacity of an activated carbon is a more useful figure. It represents the amount of adsorbate that a carbon, initially saturated, can retain when pure air is passed through the carbon with the temperature and pressure maintained constant. This indicates the weight of the particular gas or vapor that the carbon can completely retain. This is called the retentivity of the carbon and is expressed as the ratio of the weight of the adsorbate retained to the weight of the carbon.

Breakpoint

When an air vapor mixture is passed over carbon, adsorption is 100 percent at the beginning, but as the retentive capacity of the carbon is reached, traces of vapor appear in the exit air. This stage of adsorption is called the breakpoint of the carbon, beyond which the efficiency of removal decreases rapidly. As the flow of air is continued, additional amounts of solvent are adsorbed, but the concentration of vapor in the exit air (Figure 122) increases and eventually equals that in the inlet, at which time the carbon is saturated at the particular operating conditions.

Adsorption of Mixed Vapors

The adsorption phenomenon becomes somewhat more complex if the gas or vapors to be adsorbed consist of not one but several compounds. The adsorption of the various components in a mixture such as this is not uniform, and generally, these components are adsorbed in an approximately inverse relationship to their relative volatilities. Hence, when air containing a mixture of organic vapors is passed through an activated-carbon bed, the vapors are equally adsorbed at the start; but as the amount of the higher boiling constituent retained in the bed increases, the more volatile vapor revaporizes. After the breakpoint is reached, the exit vapor consists largely of the more volatile material. At this stage, the higher boiling component has displaced the lower boiling component, and this is repeated for each additional component, as shown in Figure 123. This property of activated carbon is the basis for hypersorption, a process used for the separation of low-boiling hydrocarbons. In the control of the discharge of organic vapors to the atmosphere, the adsorption cycle should be stopped at the first breakpoint as determined by the detection of vapors in the discharge.

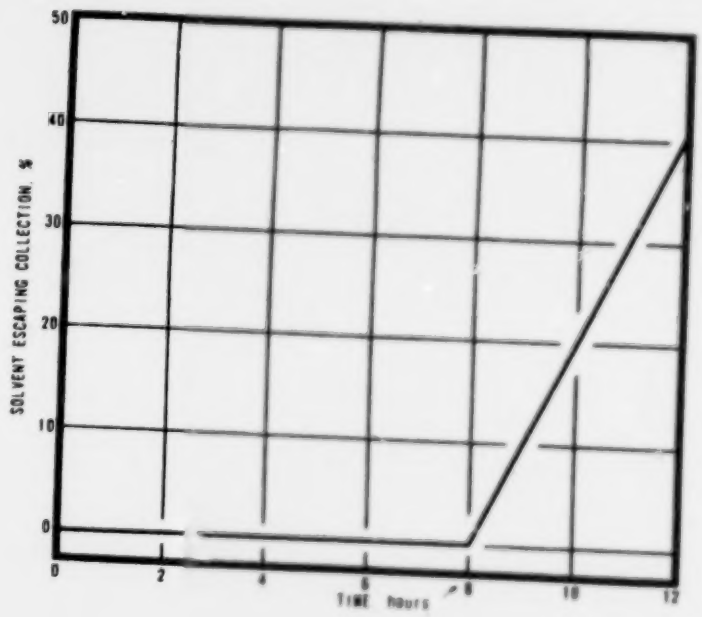


Figure 122. Adsorption efficiency, single solvent (Report No. 8, Experimental Program for the Control of Organic Emissions from Protective Coating Operations, Los Angeles County Air Pollution Control District, Los Angeles, Calif., 1961).

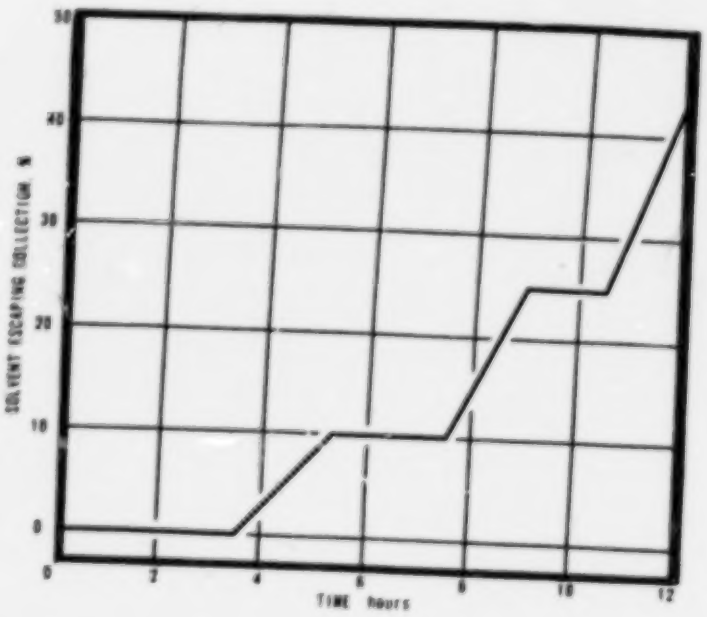


Figure 123. Adsorption efficiency, three-component lacquer solvent (Report No. 8, Experimental Program for the Control of Organic Emissions from Protective Coating Operations, Los Angeles County Air Pollution Control District, Los Angeles, Calif., 1961).

Heat of Adsorption

The amount of organic vapors adsorbed by activated carbon is a function of the boiling point, molecular weight, concentration, pressure, and temperature. Since adsorption is an exothermic process, heat is liberated, which increases the temperature of the carbon bed, and adsorption

may be necessary to provide cooling. The same result can be obtained by diluting the gas as it enters the adsorber. The vapor concentrations encountered in paint spraying or coating operations result in a temperature rise of about 15°F (Elliott et al., 1961) and do not seriously affect the capacity of the adsorbent. On the other hand, the use of activated carbon to capture vaporized organic compounds at relatively large concentrations, such as the discharge from the filling of gasoline tanks, can result in a temperature rise that can reach dangerous levels.

Carbon Regeneration

A desirable feature of using activated carbon in the control of solvent emissions is its ability to recover the adsorbed solvents on regeneration. To remove the adsorbate from the carbon, the carbon must be heated to a temperature above that at which the solvents were adsorbed. Also essential to the process is a carrier to remove the vapors released.

Regeneration is accomplished by passing a hot gas through the carbon bed. Saturated steam at low pressure, up to 5 psig, is the usual source of heat and is sufficient to remove most solvents. Steam superheated to as high as 650°F may, however, be necessary to reactivate the carbon to its original condition (Barry, 1960). This is necessary when the solvent adsorbed contains high-boiling constituents such as are found in mineral spirits. Normally the flow of steam passes in a direction opposite to the flow of gases during adsorption.

With this arrangement, the steam passes upward through the carbon. The steam through the bed is only 1/5 to 1/10 of the air velocity and is too low to initiate any boiling or cratering of the bed. This countercurrent flow is an advantage in regeneration because a solvent gradient exists across the adsorbent bed and, depending on the concentration of adsorbate and bed depth, the inlet side of the bed may be saturated before the outlet reaches the breakpoint. Thus, with countercurrent regeneration, the solvent, driven out of the adsorbent from the outlet side by the incoming steam, will in turn start to remove vapor at the inlet before it becomes heated, since it is already saturated. This results in lower steam consumption.

Steam requirements depend on external heat losses as well as the nature of the solvent. The heat liberated during adsorption is greater (Mantell, 1961) than the heat of liquefaction, and this difference may be large with an active adsorbent. The steam consumption per pound of solvent varies with time and the solvent adsorbed. This is shown in Figure 124. The ratio of the pounds of steam used per pound of perchloroethylene recovered is plotted for 15-minute intervals. This reaches a minimum of about 4.7 pounds after an elapsed time of 90 minutes and then rises sharply. The pounds of solvent recovered reaches a maximum at this time and then decreases. In Figure 124, the desorbing of toluene follows the same pattern except that the steam consumption is higher. This is to be expected since its latent heat is greater.

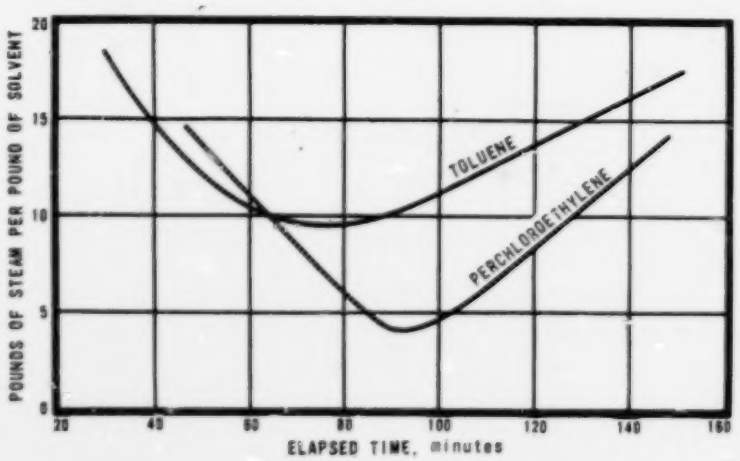


Figure 124. Steam consumption per pound of solvent recovered (Report No. 8, Experimental Program for the Control of Organic Emissions from Protective Coating Operations, Los Angeles County Air Pollution Control District, Los Angeles, Calif., 1961).

After the solvent is stripped, the carbon is not only hot but is saturated with water. Cooling and drying are usually done by blowing solvent-free air through the carbon. The ensuing evaporation of the moisture is helpful in removing the heat in the carbon. In surface-coating operations, where the solvent vapors may contain some relatively high-boiling constituents, high-temperature stripping of the carbon is periodically necessary to remove these compounds. Superheated steam of about 650°F is required (Elliott et al., 1961), or the capacity of the carbon is eventually reduced. Air must not be used in cooling the carbon under these conditions because of danger of a fire or an explosion.

EQUIPMENT DESIGN

Barry (1960), reviewing the latest developments on evaluating adsorption as a unit operation,

concludes that adequate design and scaleup procedures are not available in the chemical literature. Manufacturers of adsorbents have, however, accumulated much information on a confidential basis with their clients. For the larger percentage of processes discharging organic vapors to the atmosphere, such as dry cleaning, degreasing, paint spraying, tank dipping, and solvent extracting, packaged equipment is available that is suitable if certain precautions are taken. These factors are discussed in the following paragraphs.

A research program also was undertaken by the Los Angeles County Air Pollution Control District in conjunction with the United States Public Health Service (Elliott et al., 1961) to develop some much-needed design data and evaluate methods for the removal of organic air contaminants.

In the capture and removal of organic compounds, the vapor-laden air is passed through a layer of activated carbon. The layer can be either fixed or movable. The enclosure for a simple fixed bed may be a vertical or a horizontal cylindrical vessel. If more than one carbon bed in a single vessel is used, the beds are usually arranged as shown in Figure 125. Multiple beds such as these are best suited to a vertical vessel. Another type of fixed bed is arranged in the shape of a cone, as shown in Figures 126 and 127. It can be used in either a vertical or horizontal enclosure and has certain advantages over the flat bed, as enumerated later in this section.

A movable bed is shown in Figures 128 and 129. In this design, the carbon bed is contained in a drum, which rotates within an enclosure.

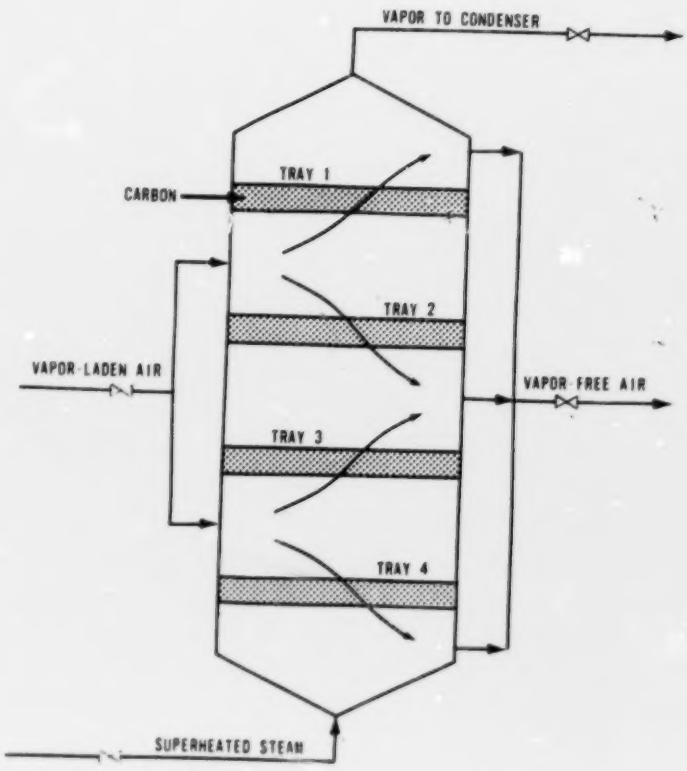


Figure 125. Cross-section of adsorber with four fixed beds of activated carbon (Report No. 8, Experimental Program for the Control of Organic Emissions from Protective Coating Operations, Los Angeles County Air Pollution Control District, Los Angeles, Calif., 1961).

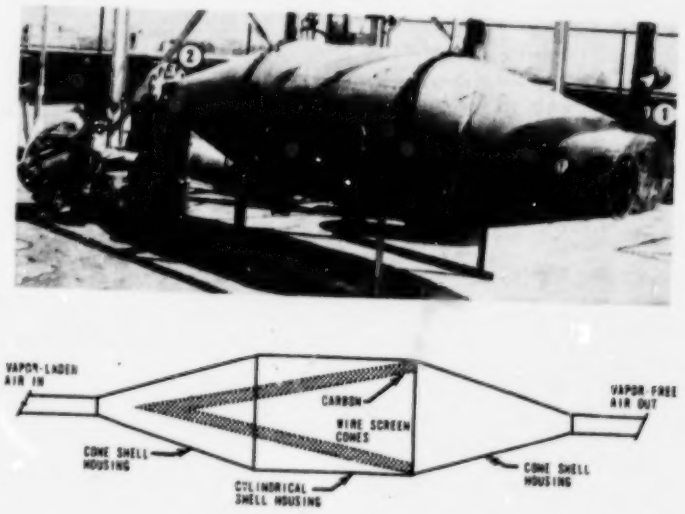
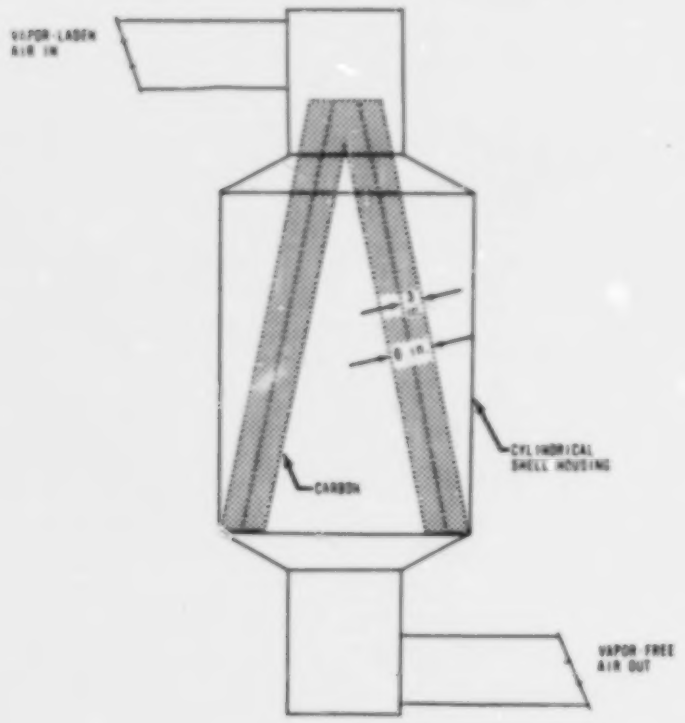


Figure 126. Top: Horizontal adsorber on the desorbing cycle with the superheated steam entering at the apex (1). Condenser is located at the vapor outlet (2). Bottom: Horizontal carbon adsorber. On the adsorption cycle the vapor-laden air enters at the apex of the cone. The steam enters either at the apex or at the bottom of the cone for desorption (Report No. 3, Experimental Program for the Control of Organic Emissions from Protective Coatings, Los Angeles County Air Pollution Control District, Los Angeles, Calif., 1959).

Fixed-Bed Adsorber

The type of enclosure used to house an activated-carbon adsorber with a fixed bed depends primarily upon the volume of gas to be handled and the allowable pressure drop. The simplest equipment for a fixed-bed adsorber is a vertical, cylindrical vessel fitted with a perforated supporting screen for the carbon. The gas stream, containing the vapor, enters the vessel at the top and flows down through the carbon bed. Downflow allows the use of higher gas velocities. In upflow, the velocity must be maintained below a value that prevents the boiling of the carbon, since this results in cratering and attrition of the adsorbent. A single fixed bed unit is satisfactory if process downtime is available for regeneration of the carbon. The horizontal, cylindrical vessel with a bed parallel to the axis is normally used when large volumes of gas must be handled.



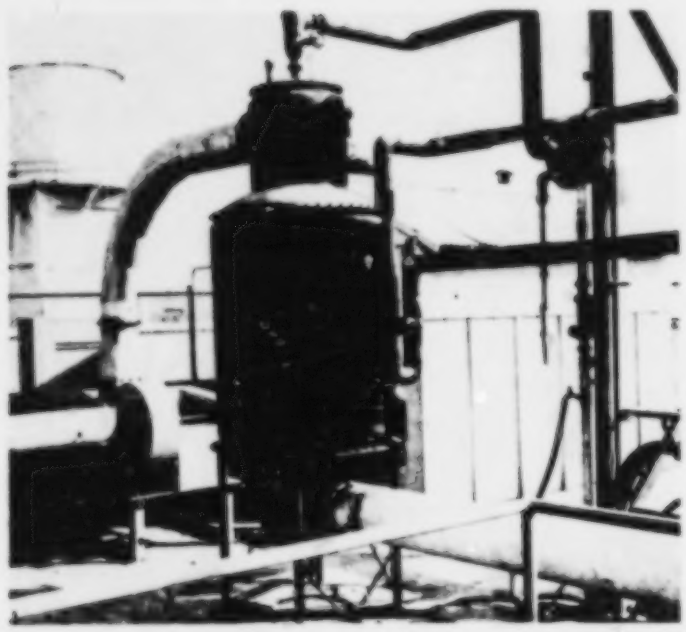


Figure 127. Top: Diagrammatic sketch of vertical adsorber with two cones, permitting studies on different depths of carbon beds. Bottom: Vertical cone adsorber in operation.

For the capture of vapors in a continuous operation, a minimum of two of these units is desirable. With this arrangement, one unit is adsorbing while the other is being stripped of solvent and regenerated. Sufficient time or means must be available to cool this unit to nearly ambient temperature before it is returned to service. A schematic diagram of this unit is presented in Figure 130. The vapor-laden air enters the first adsorber and passes downward through the carbon bed, where it is divested of its vapor, and then passes out to the atmosphere. During this period, the second adsorber is stripped of its adsorbate

Regeneration and cooling of the adsorbent usually determines the cycle time that may be used. The stripping cycle must thus allow sufficient time for the adsorbent to cool before it is returned to the adsorption system. Regeneration releases the bulk of the adsorbed vapor rapidly, the rate reaching a maximum early, then slowly trailing off as regeneration is continued. No attempt is made to remove all the adsorbate.

In Figure 131, a curve is shown in which the pounds of toluene and perchloroethylene recovered are plotted against elapsed time, and Figure 132 shows the pounds of steam per pound of solvent for each 15-minute period during stripping. The steam consumption is approximately constant (Elliott et al., 1961), and to continue heating of the carbon bed until all the solvent is removed would not be economical in terms either of steam or time. It is usually discontinued far short of this point. This does, however, reduce the capacity of the unit in the adsorption cycle.

Normally two adsorbing units are sufficient if the regeneration and cooling of the second bed can be completed before the first unit has reached the breakpoint in the adsorbing cycle.

With three units it is possible to have one bed adsorbing, one cooling, and one regenerating. Vapor-free air from the adsorbing unit is used to cool the unit just regenerated. An installation such as this is shown in Figure 133. By operating two of the units in series, greater adsorbing capacity can be realized with the same size bed. The air from the first bed, after being stripped of vapor, is passed through the second bed, which has been regenerated but is still hot and wet. By using the vapor-free air from the first unit to remove this moisture, the ensuing evaporation of the water effectively cools the carbon. After it cools, it can more effectively adsorb and the first bed can then be operated beyond its breakpoint, which increases its capacity. In the meantime the third bed is regenerated. This should be completed before the breakpoint is reached in the second bed. A fourth bed may also be used. One arrangement would be to have two units in parallel adsorbing and both discharging to a third unit, which is on the cooling cycle while the fourth unit is being regenerated. This arrangement is complex, and the increase in efficiency and capacity may not justify the added cost.

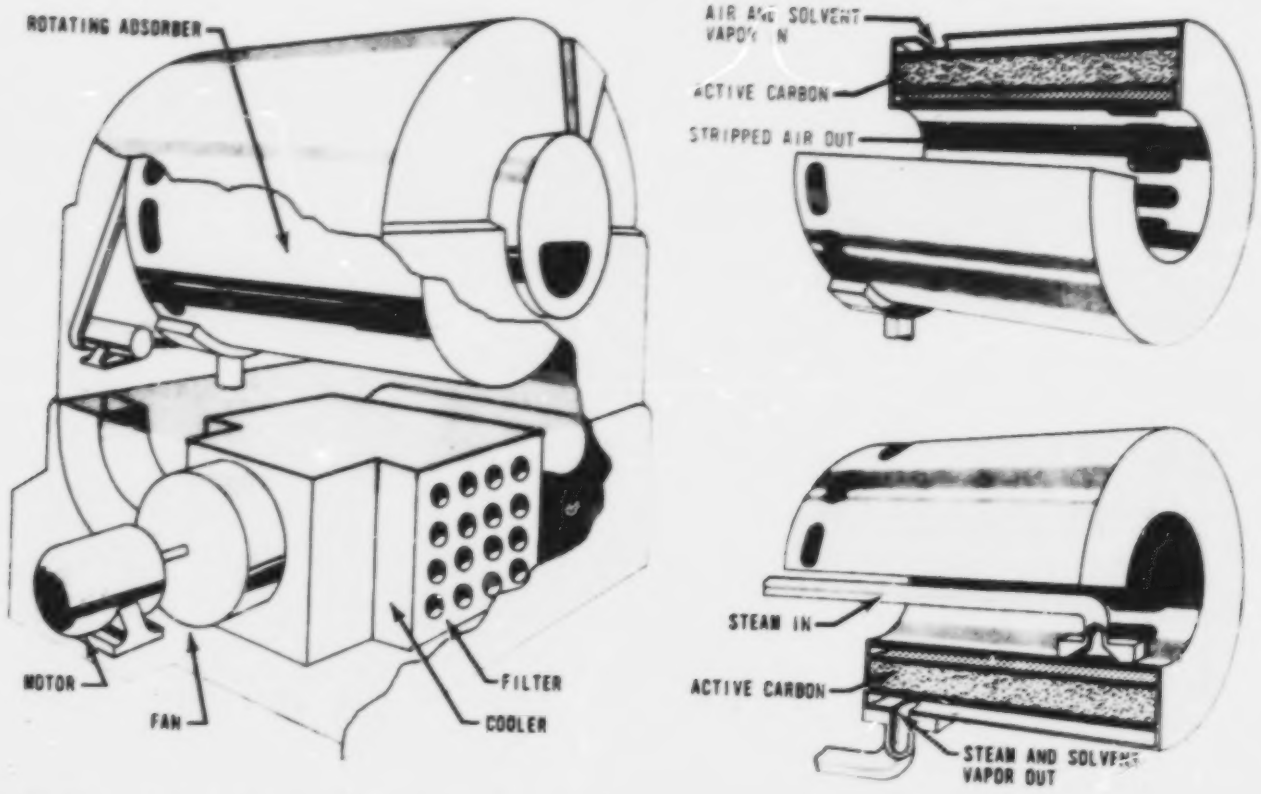


Figure 128. Left: Diagrammatic sketch of a rotating fixed-bed continuous adsorber showing the path of the vapor-laden air to the carbon bed. Right: Cut of continuous adsorber showing path of steam during regeneration (Sutcliffe, Speakman Canada, Ltd., Hamilton, Ontario).

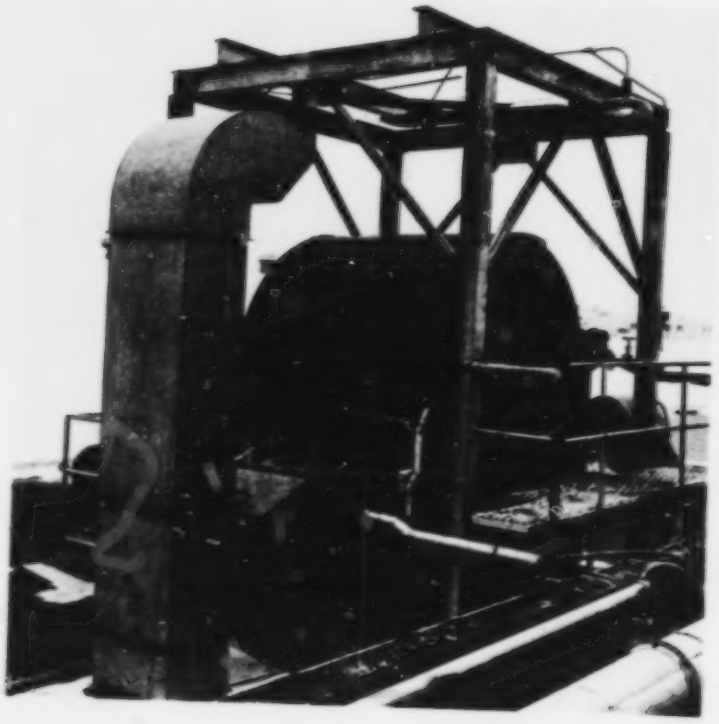


Figure 129. A continuous carbon adsorber serving a lithograph press. (Continental Can Co., Inc., Robert Gair Div., Los Angeles, Calif.).

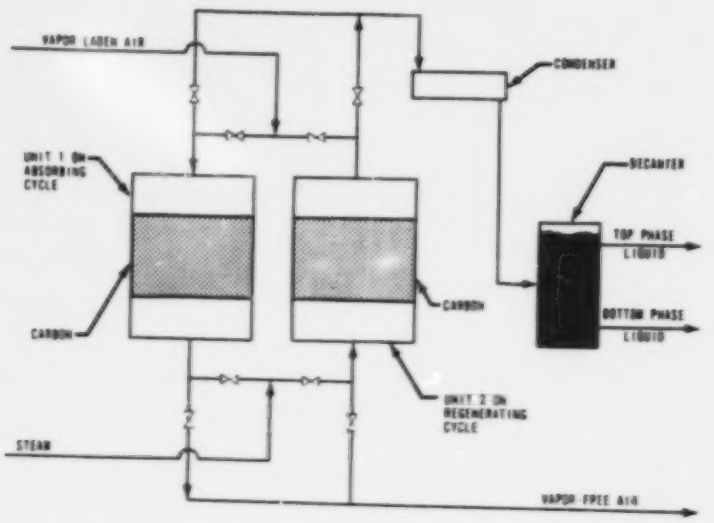


Figure 130. Diagrammatic sketch of a two-unit, fixed-bed adsorber.

Conical fixed-bed adsorber

A cone-shaped bed is one bed configuration that can be used where a relatively low pressure drop is desired (Elliott et al., 1961).

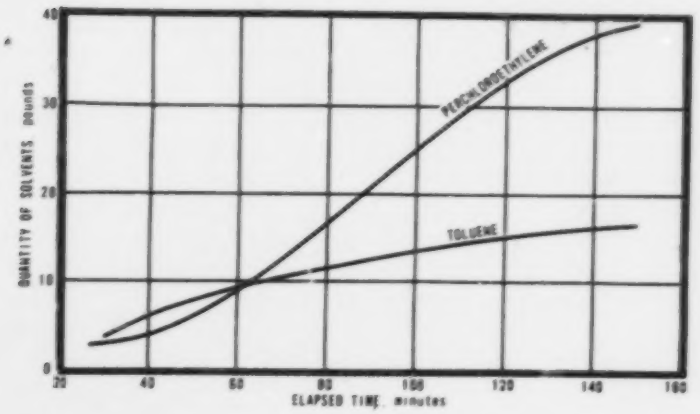


Figure 131. Pounds of solvent recovered versus time (Report No. 8, Experimental Program for the Control of Organic Emissions from Protective Coating Operations, Los Angeles County Air Pollution Control District, Los Angeles, Calif., 1961).

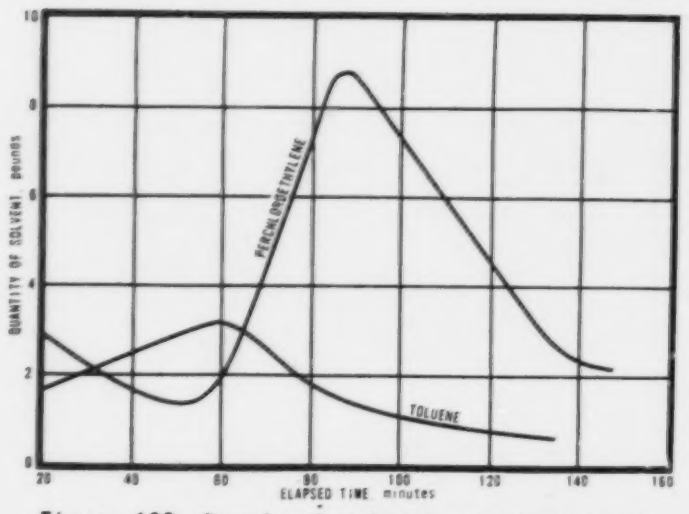


Figure 132. Pounds of solvent recovered in 15-minute intervals (Report No. 8, Experimental Program for the Control of Organic Emissions from Protective Coating Operations, Los Angeles County Air Pollution Control District, Los Angeles, Calif., 1961).

A comparison of this type of bed with a flat bed is shown in Table 56. Both beds are the same diameter and contain about the same weight of carbon, yet the pressure drop through the cone-shaped bed is less than half that through the flat bed, even when the volume of air passing through the cone-shaped bed is more than twice that through the flat bed. This cone carbon container can be modified to a cylinder configuration with similar properties.

Continuous Adsorber

A continuous, activated-carbon, solvent recovery unit is available. This unit consists of a totally enclosed, rotating drum carrying the bed. Figure 128 shows the cutaway view of the unit. The filtered air containing the solvent vapor is delivered by the fan into the enclosure and in turn enters ports to the carbon section. These ports allow the solvent-laden air to enter the area above the carbon bed. From here it passes through the bed and enters a similar space on the inside of the cylindrical bed. It then leaves this enclosure through ports located at the end of the drum opposite the entrance. The vapor-free air travels axially to the drum and is discharged to the atmosphere. The steam, in the regeneration of the carbon, enters through a row of ports by means of a slide valve as the cylinder rotates. The solvent and steam leave through a second row of ports, which is served by a similar slide valve, and are separated continuously by decantation.

Pressure Drop

The pressure drop through the carbon bed is a function of the gas velocity, bed depth, and the carbon particle size. Mantell (1961) pre-

Table 56. EXPERIMENTAL RESULTS OF FLAT- AND CONE-BED ADSORBERS

(Report No. 8, Experimental Program for the Control of Organic Emissions from Protective Coating Operations, Los Angeles County Air Pollution Control District, Los Angeles, Calif., 1961).

Adsorber type	Enclosure diameter, in.	Air volume, cfm	Air velocity through bed, fpm	Pressure drop across adsorber, in. H_2O	Weight of carbon, lb	Carbon bed depth, in.
Commercial flat bed	36	530	75	4.25	400	18
Vertical cone	36	1,350	71	1.81	352	6

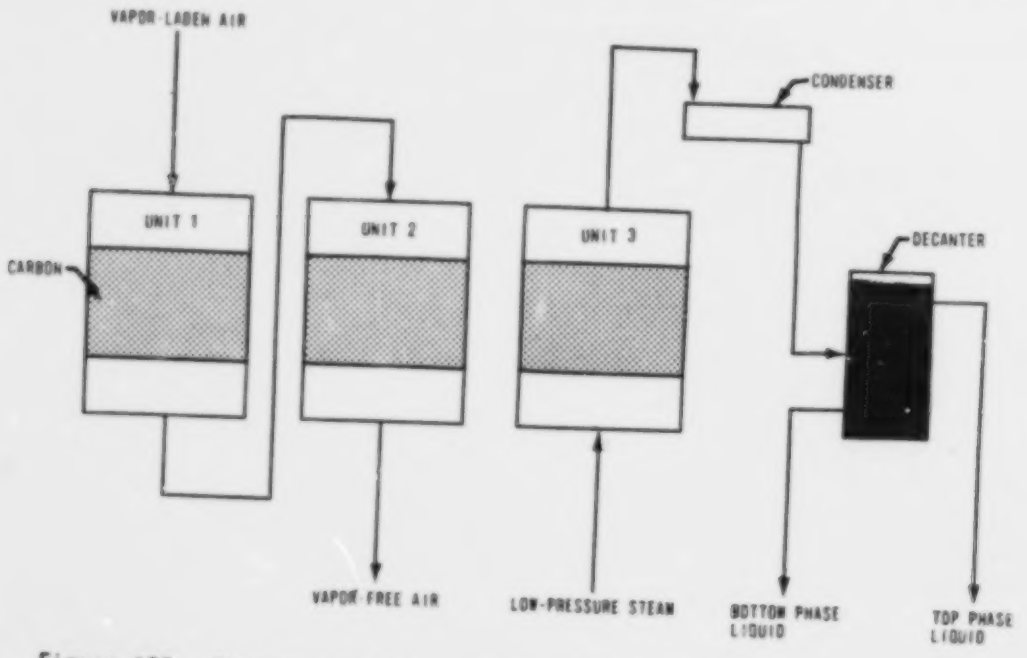


Figure 133. Diagrammatic sketch of a three-unit operation of a fixed-bed adsorber showing No. 1 and No. 2 adsorbing in series and No. 3 regenerating. Second cycle, No. 2 and No. 3 will be adsorbing with No. 1 regenerating. Final cycle, No. 3 and No. 1 will be adsorbing with No. 2 regenerating.

sents three graphs in which pressure drop in inches of water for different velocities is plotted against bed densities in pounds per square foot of bed area for several activated carbons of different meshes. Carbon Products Division, Union Carbide Corporation (1955), presents an empirical correlation representing the pressure drop through a carbon bed at air velocities from 60 to 100 fpm against bed depth in inches for two carbon mesh sizes. With this empirical formula, Figure 134 was prepared covering velocities from 60 to 140 fpm and for bed depths of 10 to 50 inches. In the Report No. 8 of the Experimental Program for the Control of Organic Emissions (1961) pressure drops for multiple-tray cone carbon adsorbers are presented based on Union Carbide Corporation's empirical correlation, as shown in Table 56. Note that, except for the horizontal-cone and four-tray adsorber, the pressure drop also includes that resulting from the abrupt directional change of the airstream at both inlet and outlet.

OPERATIONAL PROBLEMS

Particulate Matter

An activated-carbon adsorption bed should be protected from particulate matter that can coat the surface of the carbon. Without this protection, the effective area and the ability to adsorb will be impaired, and the life of the carbon will be reduced if the material is not removed by regeneration. In paint-spraying operations (Elliott et al., 1961) it was found that the carbon adsorbers could be adequately protected from particulate matter with efficient filters without excessive increase in the total pressure drop.

Corrosion

Corrosion of adsorbers occurs when steam is used in stripping solvents from activated carbon. The amount of this corrosion is intensified with increased steam temperature. Corrosion can be controlled or reduced by the use of stainless steel or by application of a protective coating of a baked phenolic resin.

Polar and Nonpolar Compounds

Polar and nonpolar solvents are equally adsorbed by activated carbon, but the recovery of polar compounds on stripping with steam requires an additional step of fractionation by distillation to effect a separation from the aqueous solution.

VAPOR CONDENSERS

Air contaminants can be discharged into the atmosphere in the form of gases or vapors. These gases or vapors can be controlled by several different methods, for example, absorption, adsorption, condensation, or incin-

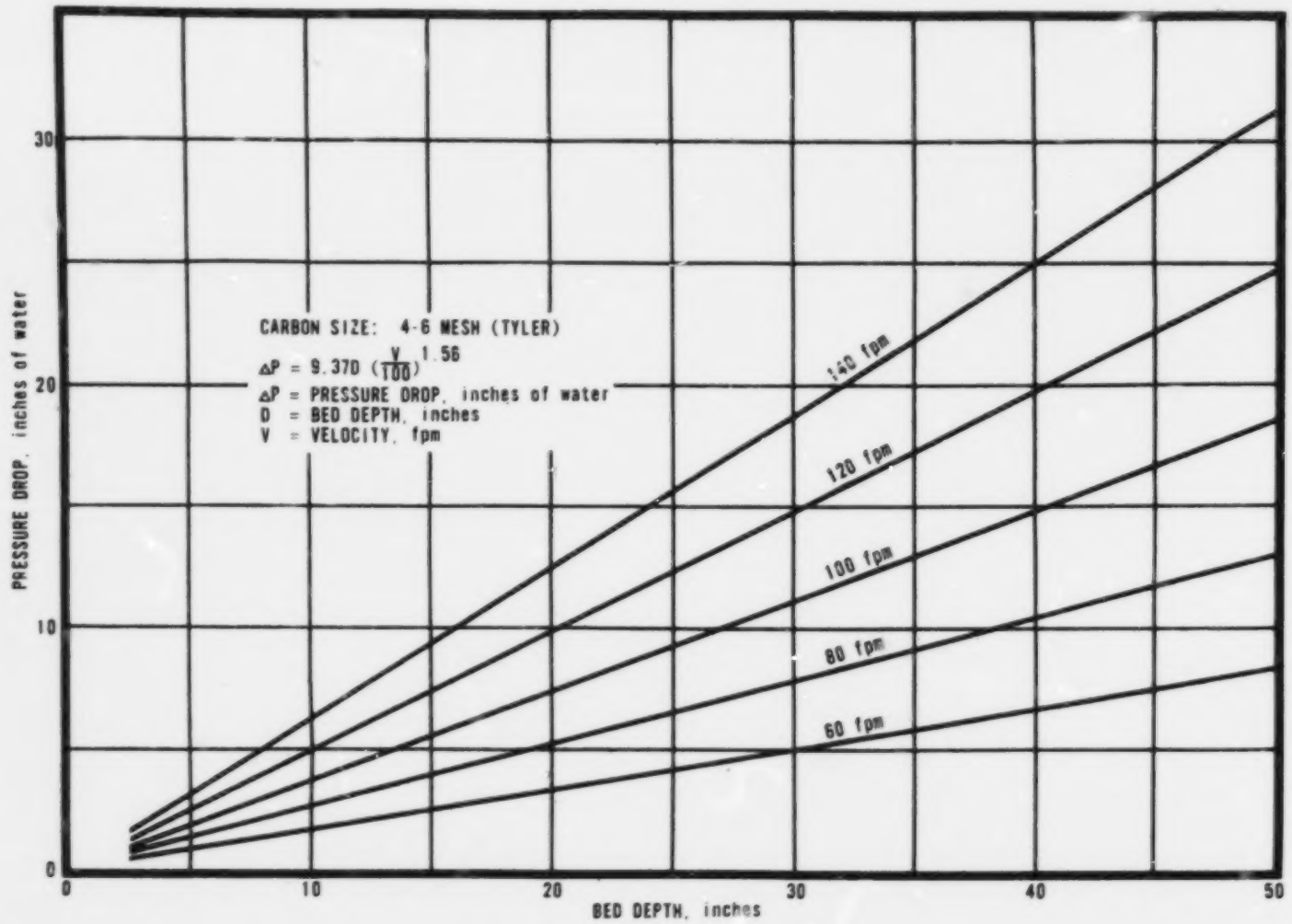


Figure 134. Pressure drop versus carbon bed depth at various air velocities (Bulletin: Solvent Recovery, 1955, Union Carbide Corporation, New York, N.Y.).

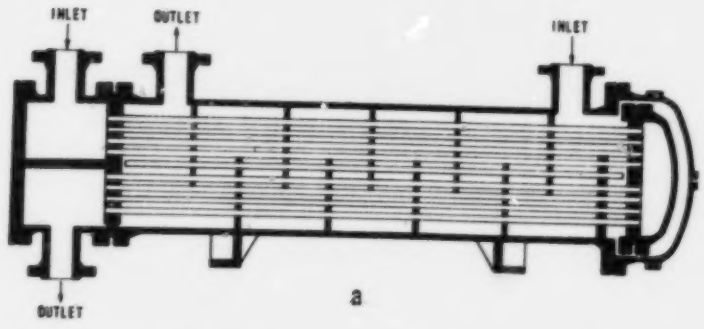
eration. In specific instances, control of vapor-type discharges can best be accomplished by condensation. Other applications require a condenser to be an integral part of other air pollution control equipment. In these cases, a condenser reduces the load on a more expensive control device or removes vapor components that may affect the operation or cause corrosion of the main control element.

TYPES OF CONDENSERS

Surface and Contact Condensers

Vapors can be condensed either by increasing pressure or extracting heat. In practice, air pollution control condensers operate through removal of heat from the vapor. Condensers differ principally in the means of cooling. In surface condensers, the coolant does not contact the vapors or condensate. In contact condensers, coolant, vapors, and condensate are intimately mixed.

Most surface condensers are of the tube and shell type shown in Figure 135a. Water flows inside the tubes, and vapors condense on the shell side. Cooling water is normally chilled, as in a cooling tower, and reused. Air-cooled surface condensers, as shown in Figure 135b, and some water-cooled units condense inside the tubes. Air-cooled condensers are usually constructed with extended surface fins. Typical fin designs are shown in Figures 135c and d. A section of an atmospheric condenser is shown in Figure 135e. Here vapors condense inside tubes cooled by a falling curtain of water. The water is cooled by air circulated through the tube bundle. The bundles can be mounted directly in a cooling tower or submerged in water. Contact condensers employ liquid coolants, usually water, which come in direct contact with condensing vapors. These devices are relatively uncomplicated, as shown by the typical designs of Figure 135f, g, and h. Some contact condensers are simple spray chambers, usually with baffles to ensure adequate contact. Others are high-velocity jets designed to produce a vacuum.

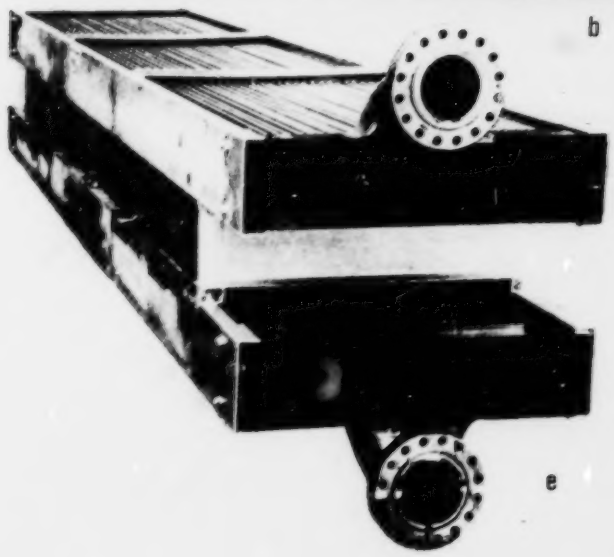


a

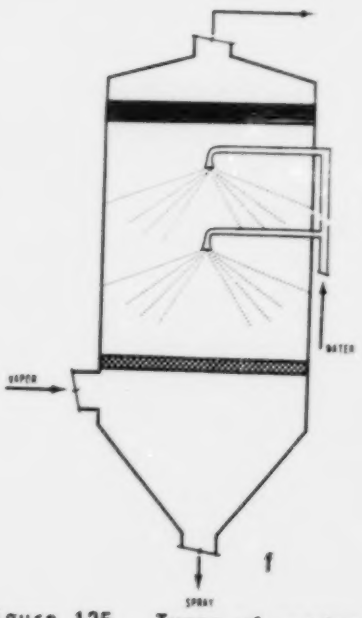
c

b

d

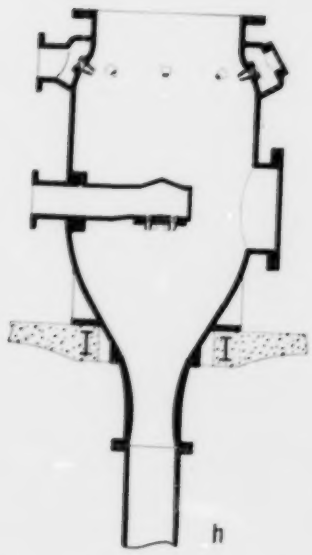


e



f

g



h

Figure 135. Types of condensers. Surface condensers: (a) Shell and tube, Schutte and Koerting Co., Cornwell Heights, Penn.,(b) fin fan, Hudson Engineering Corp., Houston, Texas, (c) finned hairpin section, Brown Fintube Co., Elyria, Ohio, (d) integral finned section, Calumet & Hecla Inc., Allen Park, Mich.,and (e) tubular, Hudson Engineering Corp.,Houston, Texas. Contact condensers: (f) Spray, (g) jet, Schutte and Koerting Co., Cornwell Heights, Penn., and (h) barometric, Schutte and Koerting Co., Cornwell Heights, Penn.

In comparison with surface condensers, contact condensers are more flexible, are simpler, and considerably less expensive to install. On the other hand, surface condensers require far less water and produce 10 to 20 times less condensate. Condensate from contact units cannot be reused and may constitute a waste disposal problem. Surface condensers can be used to recover salable condensate, if any. Surface condensers must be equipped with more auxiliary equipment and generally require a greater degree of maintenance.

Contact condensers normally afford a greater degree of air pollution control than surface condensers do because of condensate dilution. With direct-contact units, about 15 pounds of 60°F water is required to condense 1 pound of steam at 212°F and cool the condensate to 140°F. The resultant 15:1 dilution greatly reduces the concentration and vapor pressure of volatile materials that are miscible or soluble in water.

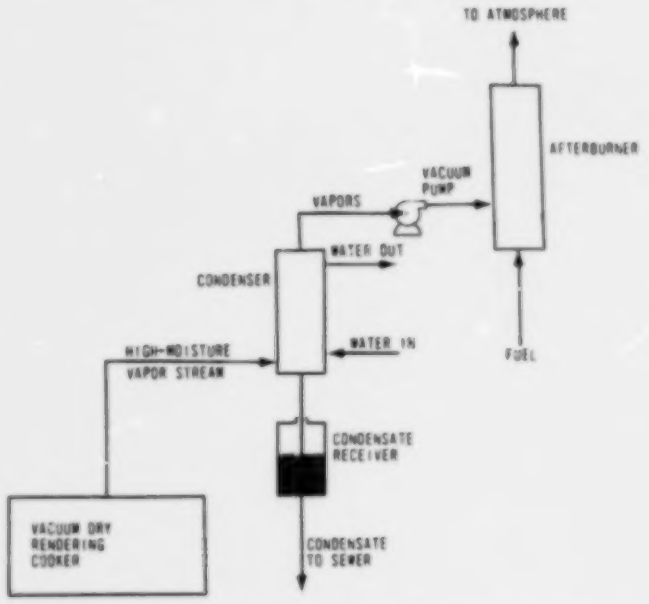


Figure 136. A condenser-afterburner air pollution control system in which a vacuum pump is used to remove uncondensed gases from condensate.

TYPICAL INSTALLATIONS

Condensers in Control Systems

Condensers collect condensable air contaminants and materially reduce the volume of contaminated gas streams containing condensable vapors. To a degree condensers are also scrubbers, contact units being generally more effective as scrubbers than surface condensers are. Probably their most common application is as an auxiliary to afterburners, adsorbers, baghouses, and other control devices. A number of possible combinations are shown in Figures 136, 137, and 138. Designs depend on the particular air contaminants and condensable vapors and on their concentrations in the contaminated stream.

The system shown in Figure 136 is designed to control odorous gases contained in a high-moisture gas stream, as from a rendering cooker or blood cooker. The stream might contain from 60 to 99 percent steam at temperatures near 212°F. At the condenser, vapors are liquefied at the boiling point. If a strong vacuum is maintained, condensing temperatures may be well below 212°F. Subcooling may also occur. Uncondensed gases are separated at the condenser and directed to an afterburner through a vacuum pump. A volume reduction of 95 percent and greater can be effected through use of either a contact or surface condenser. Some air contaminants may condense and others may be dissolved in the condensate. A contact condenser, because of greater condensate

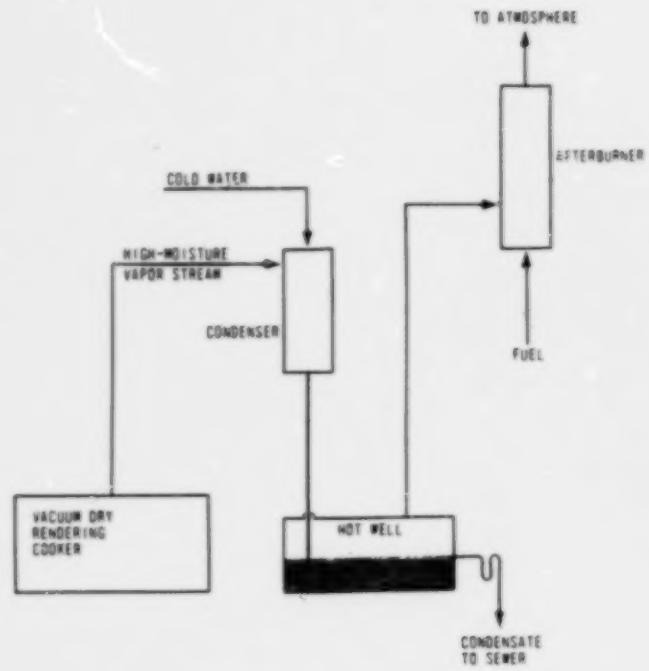


Figure 137. A contact condenser-afterburner air pollution control system in which malodorous, uncondensed gases are separated from condensate in a closed hot well.

dilution, generally removes more air contaminants than a surface condenser does.

The system shown in Figure 136 can be used with a contact or surface condenser. In either case a 32-foot barometric leg is required to pull a strong vacuum. Other vacuum devices, such as steam or water ejec-

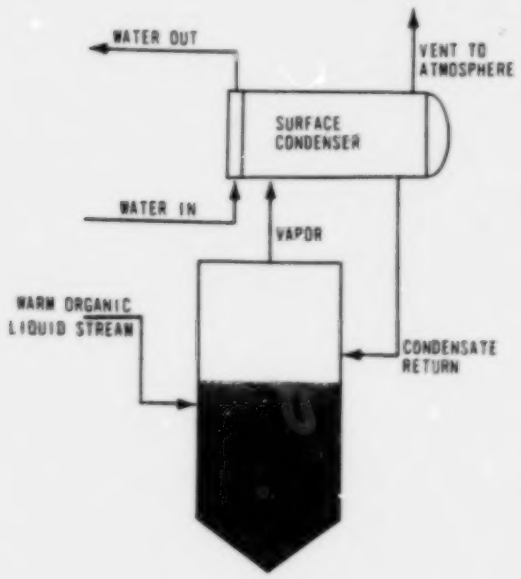


Figure 138. A surface condenser used to prevent surge losses from an accumulator tank handling warm, volatile, organic liquid.

tors, might be used in lieu of a vacuum pump. With steam ejectors, intercondensers and aftercondensers are often required. The latter auxiliary condensers might require closed hot wells to separate uncondensed gases from condensate.

A variation is shown in Figure 137. Here a contact condenser is used to control high-moisture, odorous gases. Both condensate and entrained gases drain to a closed hot well where malodorous gases separate by gravity. Liquids are removed through a trap while gases are vented to an afterburner or other suitable control device. The system of Figure 137 can be used with surface condensers but is more adaptable to contact units where adequate subcooling can be readily achieved.

The surface condenser arrangement shown in Figure 138 is used to prevent the emission of condensable organics from blending tanks, accumulator tanks, drying cleaning equipment, and so forth. This arrangement is adaptable to streams rich in condensable vapors. The condenser is mounted in the tank vent. Condensate is allowed to drain to storage or to the original source. No secondary controls are shown; however, if further control is required, the saturated gas stream from the condenser can be vented to a carbon adsorber, afterburner, or flare for final cleaning. The product recovered often offsets the cost of the condenser.

Subcooling Condensate

When condensers are used as air pollution control devices, care should be taken to ensure that there is no major evolution of volatiles from the discharged condensate. Uncondensable air contaminants should be either safely dissolved in condensate or vented to further control equipment. In most instances the condensate is merely cooled to a temperature at which the vapor pressure of contained air contaminants is satisfactorily low. The required temperature varies with the condensate. Most condensed aqueous solutions should be cooled to 140°F or less before they come into contact with the atmosphere. For volatile organics, lower temperatures are required.

In general, subcooling requirements are more stringent for surface units than for contact condensers where dilution is much greater. Nevertheless, many surface condenser designs do not permit adequate condensate cooling. In the typical water-cooled, horizontal, tube-and-shell condenser of Figure 135a, the shell side temperature is the same throughout the vessel. Vapors condense, and condensate is removed at the condensation temperature, which is governed by pressure. In a horizontal-tube unit of this type, condensate temperature can be lowered by: (1) Reducing the pressure on the shell side, (2) adding a separate subcooler, or (3) using the lower tubes for subcooling as shown in Figure 139. Reducing the pressure alters operating variables in the basic equipment and is not feasible in many instances. The arrangement of Figure 139 is adaptable to most processes though it reduces the heat

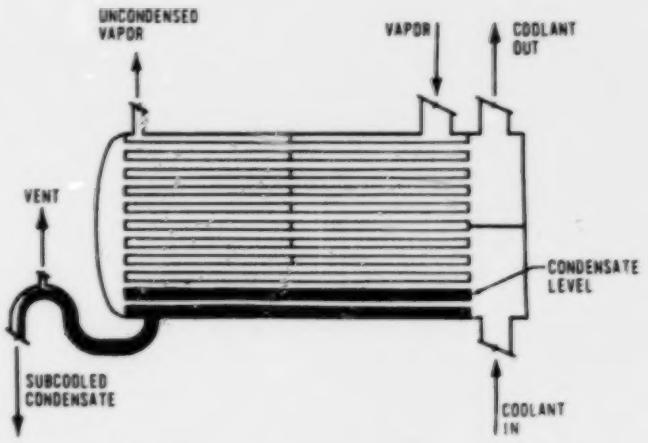


Figure 139. Maintaining a condensate level above the lower tubes to provide subcooling in a horizontal tube-and-shell condenser.

transfer area available for condensation. Here a level of condensate is maintained in the condenser shell. Condensate is chilled before being discharged through the trap.

The latter arrangement can be used with vertical-tube units, though it may not be necessary. Vertical-tube condensers provide some degree of subcooling even with condensation on the shell side.

With condensation inside the tubes, subcooling occurs in much the same manner whether tubes are arranged vertically or horizontally. With inside-the-tube condensation, both condensate and uncondensed vapors pass through the full tube length. A separate hot well is usually provided to separate gases before condensate is discharged.

CONTACT CONDENSERS

Sizing Contact Condensers

Water requirements for contact condensers can be calculated directly from the condensation rate, by assuming equilibrium conditions. The cooling water (or other medium) must absorb enough heat to balance the heat of vaporization and condensate subcooling. Piping and hot wells must be sized on the maximum condenser requirement. The following example illustrates the method of calculating the quantity of cooling water for a specific service.

Example 24

Given:

Malodorous exhaust vapors from a dry rendering cooker contain 95 percent steam at 200°F at 11.5 psia. The maximum evaporation rate in the cooker is 2,000 lb per hour. Steam is to be condensed at 200°F and cooled to 140°F in a contact condenser. A vacuum pump removes uncondensable vapors at the condenser and maintains a slight vacuum on the cooker.

Problem:

Calculate the volume of 60°F fresh water required and the resultant condensate volume.

Solution:

Condensation: 2,000 x 977.9 Btu/hr = 1,960,000 Btu/hr

Subcooling: 2,000 (200-140) Btu/hr = 120,000 Btu/hr

Cooling load 2,080,000 Btu/hr

$$\text{Water requirement} = \frac{2,080,000 \text{ Btu/hr}}{(140-60) \text{ Btu/lb}}$$

$$= 26,000 \text{ lb/hr}$$

$$= 51.4 \text{ gpm}$$

$$\text{Total condensate} = 51.4 + \frac{2,000 \text{ lb/hr}}{60 \times 8.33 \text{ lb/gal}}$$

$$= 55.4 \text{ gpm}$$

SURFACE CONDENSERS

Characteristics of Condensation

Condensation occurs through two distinct physical mechanisms, dropwise and filmwise condensation. When a saturated pure vapor comes in contact with a sufficiently cold horizontal surface, the vapor condenses and forms liquid droplets on the surface. These droplets fall from the surface, leaving bare metal exposed on which successive condensate drops may form. This is dropwise condensation.

Normally, a film occurs and coats the condensing surface. Additional vapors must then condense on this film rather than on the bare metal surface. This is called filmwise condensation and occurs in most condensation processes. Heat transfer coefficients are one-fourth to one-eighth the transfer units associated with dropwise condensation (Kern, 1950).

Steam is the only pure vapor known to condense in a dropwise manner. Dropwise condensation has been found to take place at various times when a mixture of vapors and gases is present. Some degree of dropwise condensation may possibly be attained by using certain promoters. Promoters such as oleic acid on nickel or chrome plate, and benzyl mercaptan on copper or brass become absorbed on the surface as a very thin layer to prevent the metal surface from being wetted by any condensate. Steel and aluminum surfaces are difficult to treat to acquire dropwise condensation. Use of these promoters increases the heat transfer coefficient to 6 to 10 times the amount of filmwise coefficients (Perry, 1950).

Design of Surface Condensers

Nearly all condenser design calculations are based on heat transfer that is affected by an overall transfer coefficient, temperatures, and surface area. A mathematical solution to the problem is usually achieved by the expression

$$Q = UAT_m \qquad (85)$$

where

Q = heat transferred, Btu/hr

U = overall coefficient, Btu/hr per ft^2 per °F

A = heat transfer, ft^2

T_m = mean temperature difference, °F.

Condenser design is often more difficult than indicated by the foregoing expression, and a simplified or general overall heat transfer coefficient is not used. This is especially true when a vapor is condensed in presence of a noncondensable gas (Donahue, 1956). Nusselt relations were developed for streamlined flow of all vapor entering vertical- or horizontal-tube exchangers. These equations* account for the variation of the film thickness (thinnest at top of the tube and tube bundle of vertical and horizontal exchangers) by expressing the vapor side mean heat-transfer coefficient in terms of condensate loading. The equations are based only upon vapor entering the condenser and are as follows:

Kind of surface	Mean heat transfer coefficient, h_m
Vertical-tube bundle	$0.925\left[\frac{k^3 \rho^2 g \pi D}{\mu w}\right]^{1/3}$
Horizontal-tube bundle	$0.955\left[\frac{k^3 \rho^2 g L}{\mu w}\right]^{1/3}$

In instances of streamlined flow of condensate, the heat-transfer coefficient has been established as inversely proportional to film thickness. Observations have, however, shown a decrease to a certain point, and then a reverse effect when the coefficient increased. This reversal occurred at a Reynolds number of approximately 1,600, indicating that turbulence in liquid film increases the heat transfer coefficient. Figure 140 shows the relationship between the coefficient and Reynolds number.

A temperature profile of vapor condensing in the presence of a noncondensable gas on a tube wall, as shown in Figure 141, indicates the resistance to heat flow. Heat is transferred in two ways from the vapor to the interface. The sensible heat is removed in cooling the vapor from t_v to t_c at the convection gas cooling rate. The latent heat is removed only

*Symbol notations for these equations are defined at the end of this chapter on page 232.

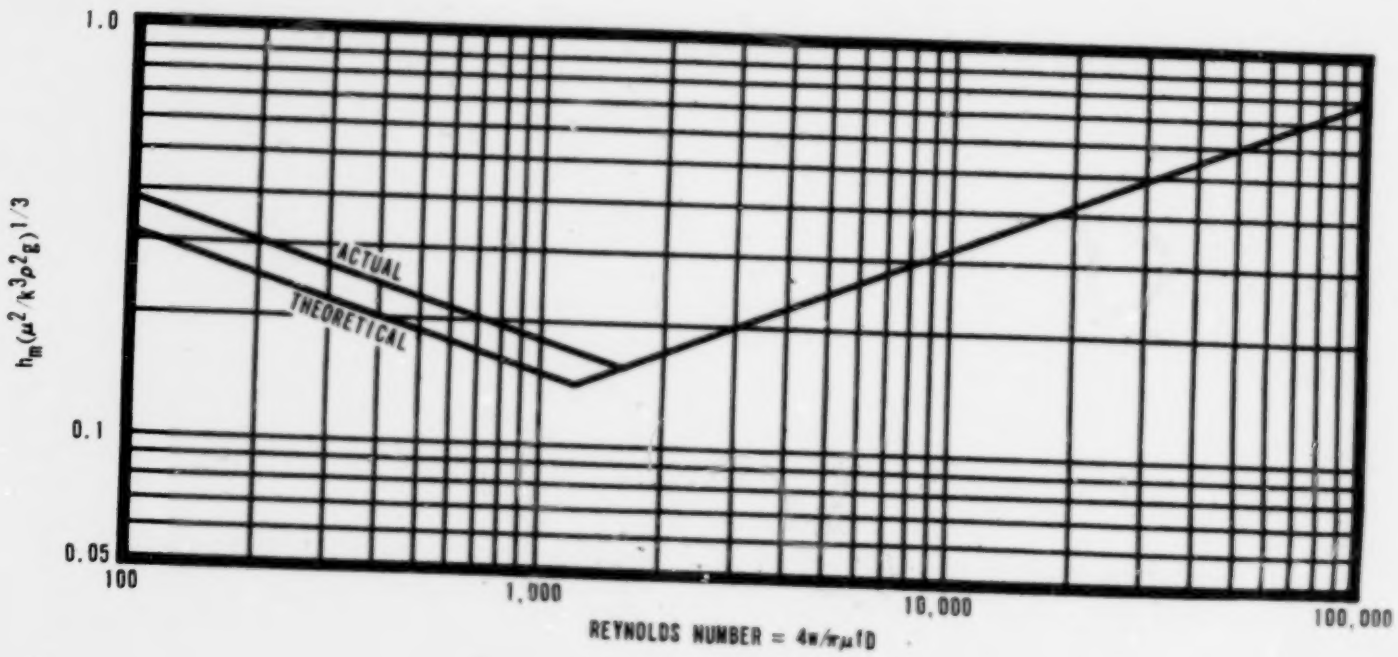


Figure 140. Heat-transfer coefficient of condensation (Donahue, 1956).

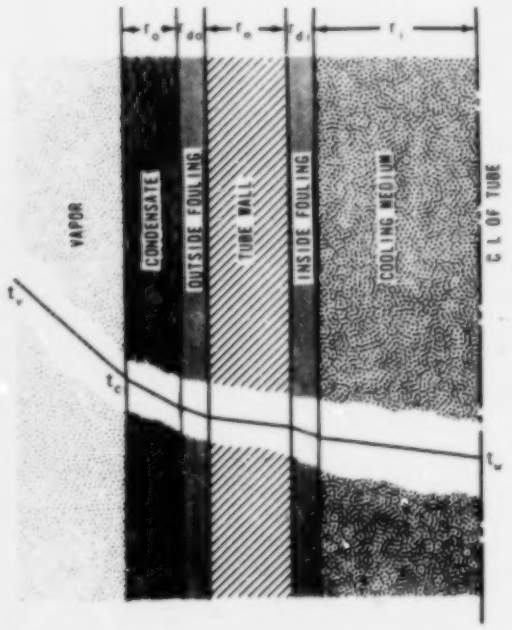


Figure 141. Temperature profile showing effect of vapor condensation on a tube wall in presence of a noncondensable gas.

after the condensable vapor has been able to diffuse through the noncondensable part to reach the tube wall. This means the latent heat transfer is governed by mass transfer laws.

By using a heat balance around the interface, the following equation is obtained:

$$h(t_v - t_c) + KM_v \lambda (p_v - p_c) = U_c(t_c - t_w) \quad (86)$$

When condensation of a pure vapor occurs, $t_c = t_v$. When a condensable gas is present, however, t_c is lower than t_v. In solving this equation, a value of t_c is selected by trial and error to satisfy the equilibrium condition. The calculation is repeated for different points in the condenser. The surface area necessary is found by using U_c and a mean temperature based on t_c and t_w over the entire condensing range.

Simultaneous heat and mass transfer must be used to evaluate the equilibrium equation. The following basic relations state the analogy between friction, heat transfer, and mass transfer:

For friction:

$$j_f = 1/2f \quad (87)$$

For heat transfer:

$$j_h = \frac{h}{cG}\left[\frac{c\mu}{k}\right]^{2/3} \quad (88)$$

For mass transfer:

$$j_D = \frac{K_p}{G} BM \left[\frac{\mu}{\rho D_v}\right]^{2/3} M_m \quad (89)$$

Flow inside tubes:

$$j = j_f = j_h = j_D = \frac{0.027}{\left[\frac{D_i G_i}{\mu}\right]^{0.2}} \quad (90)$$

Flow across tube banks:

$$j = j_f = j_h = j_D = \frac{0.33}{\left[\frac{DG_c}{\mu}\right]^{0.4}} \quad (91)$$

For solving equation 86, the following procedure is recommended:

1. Using Raoult's law of partial pressures, calculate the amount of vapor condensing at inlet and outlet temperatures, and at least three intermediate temperatures
2. Obtain the following physical properties at the average of inlet and outlet temperatures and pressures: μ, ρ, D_v, M_m, M_v, λ, c, k, $(c\mu/k)^{2/3}$, and $(\mu/\rho D_v)^{2/3}$
3. Choose trial unit
4. Calculate G_c, G_b, and G_e
5. Calculate $\Delta\rho_c + \Delta\rho_b = \Delta\rho_s$
6. Calculate h from equation:

$$\frac{hD}{k} = 0.22\left[\frac{DG_e}{\mu}\right]^{0.6}\left[\frac{c\mu}{k}\right]^{1/3}\left[\frac{\mu}{\mu w}\right]^{0.14}$$

7. Calculate U_c
8. Calculate j, (for segmentally baffled shell

$$j = \frac{0.22}{\left[\frac{DG_e}{\mu}\right]^{0.4}}$$

9. Calculate K from equation:

$$K = \frac{j_G}{M_m p_{BM}\left[\frac{\mu}{\rho D_v}\right]^{2/3}}$$

$$p_{BM} = \frac{(P - p_c) - (P - p_v)}{\ln \frac{(P - p_c)}{(P - p_v)}} = \frac{(p_v - p_c)}{\ln \frac{(P - p_c)}{(P - p_v)}}$$

10. Corresponding to the inlet t_v, select by T and E, t_c to balance equation (87)

11. Find t_c in same manner for other points

12. Calculate the heat removed between each two successive temperature points, including condensate cooling

13. Between each two successive temperature points, calculate Δt based on the temperature difference between t_c and t_w

14. Using U_c, find the heat transfer surface required between two successive temperature points, using Δt from step 13.

The preceding discussion pertains to the design of a condenser for condensation of vapor in presence of a noncondensable gas. The design of the many types of condensers is a vast field and much too lengthy to cover in this text. Many technical reference books and articles have been published containing condenser design and cost data (Chilton, 1949; Diehl, 1957; How, 1956; Friedman, 1959; Kern, 1950; Nelson, 1958; Perry, 1950; Smith, 1958; and Thomas, 1959).

Some pertinent facts compiled from these and other references that will assist in handling condenser problems include (Kern, 1950):

1. Any saturated vapor can be condensed by a direct spray of cold water under correct temperature and pressure. If sufficient contact is provided, coolant and vapor will reach an equilibrium temperature. The condensate created by the water should not be objectionable in its liquid form.

2. Pure vapor or substantially pure vapor can be considered condensed isothermally, and during the condensate range the latent heat of condensation is uniform.

3. If the temperature range of a mixture does not exceed 10° to 20°F, condensation of this mixture may be treated as a pure component.

4. In condensation of streams consisting primarily of steam, the condenser size ranges from 10,000 to 60,000 square feet per shell (bundle), the tubes averaging 26 feet long.

5. In water-cooled tube-and-shell condensers with shell side condensation, overall heat transfer coefficients for essentially pure steam range from 200 to 800 Btu per hour per square foot per °F.

6. With tube side condensation, coefficients are generally lower than for comparable shell side condensers. This phenomenon is attributed to: (1) Lower coolant velocities outside the tubes than are possible with tube side cooling, and (2) increased film thicknesses, namely, film resistances inside the tubes.

7. Noncondensable gases at condenser temperature blanket the condenser surface and reduce the condenser capacity.

8. Condensation reduces the volume of the vapor present and can be assumed to occur at a constant pressure drop.

9. A balanced pressure drop may be assumed in the horizontal condenser where partial condensation is occurring.

10. Within low-pressure operating ranges, the slight pressure loss due to friction in vapor pipes may mean an appreciable loss of total available temperature difference (Perry, 1950).

11. Low-density steam under vacuum conditions can cause a linear velocity to be higher than is allowable with steam lines (Perry, 1950).

12. Vapors should travel across the bundle as fast as possible (Kern, 1950).

13. Air or inerts can cause up to 50 percent reduction in condensation coefficients (Kern, 1950; Perry, 1950).

14. Sources of air or inerts include: Dissolved gas in the cooling water in cases of jet condensers, entrainment with steam, entrainment with vapor, leaks, and noncondensable gases (Perry, 1950).

15. In vertical-tube condensers, 60 percent of the condensation occurs in the upper half (Kern, 1950).

16. Horizontal position of a condenser distributes the vapor better and permits easier removal of the condensate (Kern, 1950).

17. In the horizontal condenser, it is necessary to prevent cooled condensate from forming liquid pools and impeding the flow of vapors (Kern, 1950).

18. Selection of which material should pass through tubes cannot be decided by fixed rules, because of factors at a variance with one another. When corrosive condensate is encountered, condensation within the tubes rather than the shell is usually desirable (Nelson, 1958).

APPLICATIONS

Condensers have been used successfully (either separately or with additional control equipment) on the following processes or equipment:

REFINERY AND PETROCHEMICAL

Alkylation unit accumulator vents

Amine stripper units

Butadiene accumulator vents

Coker blowdown

Ketone accumulator vents

Lube oil rerefining

Polyethylene gas preparation accumulator vents

Residium stripper unit accumulator vents

Storage equipment

Styrene-processing units

Toluene recovery accumulator vents

Udex extraction unit

CHEMICAL

Manufacture and storage of ammonia

Manufacture of Cooper naphthenates

Chlorine solution preparation

Manufacture of ethylene dibromide

Manufacture of detergent

Manufacture of insecticide

Manufacture of latex

Manufacture of nitric acid

Manufacture of phthalic anhydride

Resin reactors

Soil conditioner formulators

Solvent recovery

Thinning tanks

MISCELLANEOUS

Aluminum fluxing

Asphalt manufacturing

Blood meal driers

Coal tar-dipping operations

Degreasers

Dry cleaning units

Esterfication processes

Pectar preparation

Rendering cookers (animal waste)

Vitamin formulation

GAS ABSORPTION EQUIPMENT

Gas absorption is the mechanism whereby one or more constituents are removed from a gas stream by dissolving them in a selective liquid solvent. This is one of the major chemical engineering unit operations and is treated extensively in all basic chemical engineering textbooks. These texts deal with gas absorption as a method of recovering valuable products from gas streams, for example, in petroleum production, natural gasoline is removed from wellhead gas steams by absorption in a special hydrocarbon oil. Absorption is also practiced in industrial chemical manufacturing as an important operation in the production of a chemical compound. For example, in the manufacture of hydrochloric acid, one step in the process involves the absorption of hydrogen chloride gas in water.

From an air pollution standpoint, absorption is useful as a method of reducing or eliminating the discharge of air contaminants to the atmosphere. Even in this application, absorption can yield profits to the user. For example, it can be employed to remove hydrogen sulfide from process gas streams in a petroleum refinery to meet air pollution regulations. With further processing, this hydrogen sulfide can be converted to elemental sulfur, a valuable product.

The gaseous air contaminants most commonly controlled by absorption include sulfur dioxide, hydrogen sulfide, hydrogen chloride, chlorine, ammonia, oxides of nitrogen, and light hydrocarbons.

In other examples, such as solvent recovery, desorption or stripping may be practiced after absorption not only to recover a valuable absorbed constituent but also to recover valuable solvent for reuse. Sometimes, after absorption, solute and solvent are not separated but are used as a product or intermediate compound in chemical manufacture.

Treybal (1955) lists some important aspects that should be considered in selecting absorption solvents.

1. The gas solubility should be relatively high so as to enhance the rate of absorption and decrease the quantity of solvent required. Solvents similar chemically to the solute generally provide good solubility.
2. The solvents should have relatively low volatilities so as to reduce solvent losses.
3. If possible, the solvents should be noncorrosive so as to reduce construction costs of the equipment.
4. The solvents should be inexpensive and readily available.
5. The solvents should have relatively low viscosities so as to increase absorption and reduce flooding.
6. If possible, the solvents should be nontoxic, nonflammable, chemically stable, and have low freezing points.

GENERAL TYPES OF ABSORBERS

Gas absorption equipment is designed to provide thorough contact between the gas and liquid solvent in order to permit interphase diffusion of the materials. The rate of mass transfer between the two phases is largely dependent upon the surface exposed. Other factors governing the absorption rate, such as solubility of the gas in the particular solvent and degree of chemical reaction, are characteristic of the constituents involved and are more or less independent of the equipment used. This contact between gas and liquid can be accomplished by dispersing gas in liquid or vice versa.

Absorbers that disperse liquid include packed towers, spray towers or spray chambers, and venturi absorbers. Equipment that uses gas dispersion includes tray towers and vessels with sparging equipment.

PACKED TOWER DESIGN

A packed tower is a tower that is filled with one of the many available packing materials, as shown in Figure 142. The packing is designed so as to expose a large surface area. When this packing surface is wetted by the solvent, it presents a large area of liquid film for contacting the solute gas.

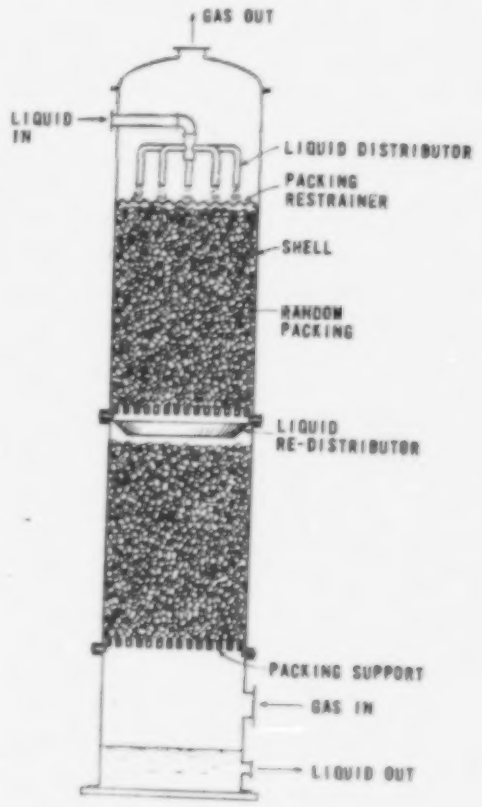


Figure 142. Schematic diagram of a packed tower (Treybal, 1955, p. 134).

Usually the flow through a packed column is countercurrent, with the liquid introduced at the top to trickle down through the packing while gas is introduced at the bottom to pass upward through the packing. This results in highest possible efficiency, since, as the solute concentration in the gas stream decreases as it rises through the tower, there is constantly fresher solvent available for contact. This gives maximum average driving force for the diffusion process throughout the entire column.

In concurrent flow, where the gas stream and solvent enter at the top of the column, there is initially a very high rate of absorption that constantly decreases until, with an infinitely tall tower, the gas and liquid would leave in

equilibrium. Concurrent flow is not often used except in the case of a very tall column built in two sections, both located on the ground, the second section using concurrent flow merely as an economy measure to obviate the need for constructing the large gas pipe from the top of the first section to the bottom of the second. Moreover, for an operation requiring an exceptionally high solvent flow rate, concurrent flow might be used to prevent flooding that could occur in countercurrent flow.

Packing Materials

The packing should provide a large surface area and, for good fluid flow characteristics, should be shaped to give large void space when packed. It should likewise be strong enough to handle and install without excessive breakage, be chemically inert, and be inexpensive.

Rock and gravel have been used but have disadvantages of being too heavy, having small surface areas, giving poor fluid flow and, at times, not being chemically inert. Coke lumps are also used sometimes and here the weight disadvantage is not present. Owing to its porosity, coke has a large surface area per unit volume. The exposed surface is not, however, as large as might be expected since the pores are so small that they become filled or filmed over by the solvent, which considerably reduces the effective surface.

Generally, packing in practice consists of various manufactured shapes. Raschig rings are the most common type, consisting of hollow cylinders having an external diameter equal to the length. Other shapes include Berl saddles, Intalox saddles, Lessing rings, cross-partition rings, spiral-type rings, and drip-point grid tiles. Figure 143 shows several common shapes. Physical characteristics of these various types of packings have been determined experimentally and compiled in tables by Leva (1953).

Packing may be dumped into the column randomly, or regularly shaped packing may be manually stacked in an orderly fashion. Randomly dumped packing has a higher specific surface contact area and a higher gas pressure drop across the bed. The stacked packings have an advantage of lower pressure drop and higher possible liquid throughout, but the installation cost is obviously higher. Table 57 and Figure 144 list typical packing costs and packed-tower installed prices for 1959.

Figure 143. Common tower packing materials (Teller, 1960, p. 122).

Table 57. COSTS OF REPRESENTATIVE TOWER PACKINGS (Teller, 1960)

Packing	Cost of packing, $/ft^3 (1959 basis)			
	1/2-in.	1-in.	1-1/2-in.	2-in.
Raschig rings, ceramic	11.70	6.50	5.05	4.85
Raschig rings, carbon	16.90	9.60	8.00	6.60
Berl saddles, ceramic	24.80	9.90	7.50	7.70
Intalox saddles, ceramic	23.55	9.40	7.15	7.30
Intalox saddles, carbon	-	18.60	18.40	-
Tellerettes, polyethylene				
Low density	-	16.00	-	-
High density	-	23.00	-	-
Pall rings, ceramic (BASF)	-	5.00	-	-
Pall rings, polypropylene	41.00	26.00	20.75	18.50
Pall rings, stainless steel	186.50	96.00	83.00	69.00

Liquid Distribution

Since the effectiveness of a packed tower depends on the availability of a large, exposed, liquid film, then obviously, if poor liquid distribution prevents a portion of the packing from being irrigated, that portion of the tower is ineffective. Poor distribution can be due to improper introduction of the liquid at the top of the tower and to channeling within the tower.

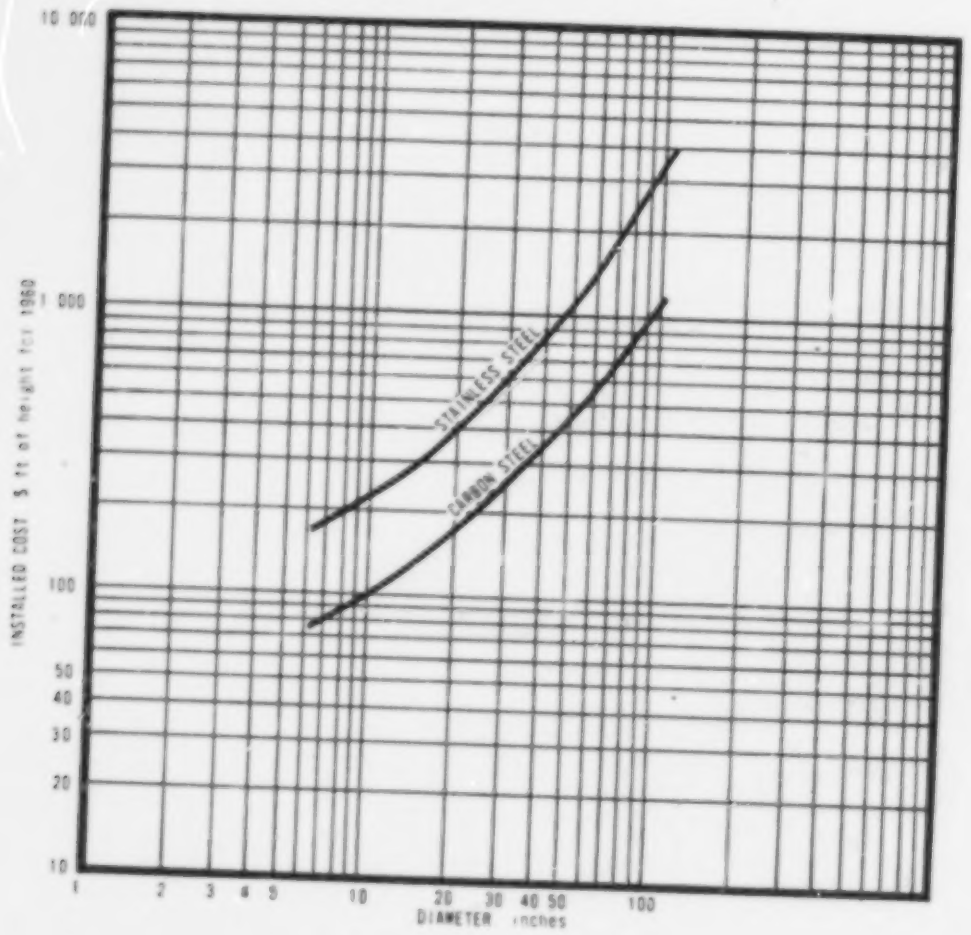


Figure 144. Packed-tower costs, 1959, with Raschig rings as packing (Teller, 1960, p. 123).

At least five points of introduction of liquid per square foot of tower cross-section must generally be provided to ensure complete wetting. The liquid rate must be sufficient to wet the packing but not to flood the tower. Treybal (1955) states that a superficial liquid velocity of at least 800 pounds of liquid per hour per square foot of tower cross-section is desirable.

Solid-cone spray nozzles make excellent distributors but may plug if solid particles are present in the solvent. In randomly packed towers, the liquid tends to channel toward the walls, because of the usually lower packing density near the walls. In tall towers this channeling is controlled by liquid redistributors at intervals of 10 to 15 feet. Moreover, this effect is minimized if the packing pieces are less than one-eighth the diameter of the tower.

Tower Capacity

The terms used to indicate capacity of a packed column or tower are load point and flood point. For a given packing and liquid rate, if gas pressure drop is plotted against gas velocity on a logarithmic scale, there are two distinct breakpoints where the slope of the curve increases. At low gas velocities the curve is almost parallel to that obtained with dry packing, but above the breakpoints, the pressure drop increases more rapidly with increased gas velocity. The lower of these two breaks is the load point and the higher one the flood point.

As gas velocity increases above the load point, the liquid holdup in the bed increases until, at the second breakpoint, the flood point, most of the void space in the tower is filled with liquid and there is liquid entrainment in the gas stream. Of course, at this point there is an excessive pressure drop. Columns should seldom be operated above the load point, but since the load point is sometimes more difficult to establish than the flood point, it is common practice to design for 40 to 70 percent of the flood point. In general, flooding velocities are considerably higher for stacked packing than for dumped packing. The plot of Lobo (Figure 145) can

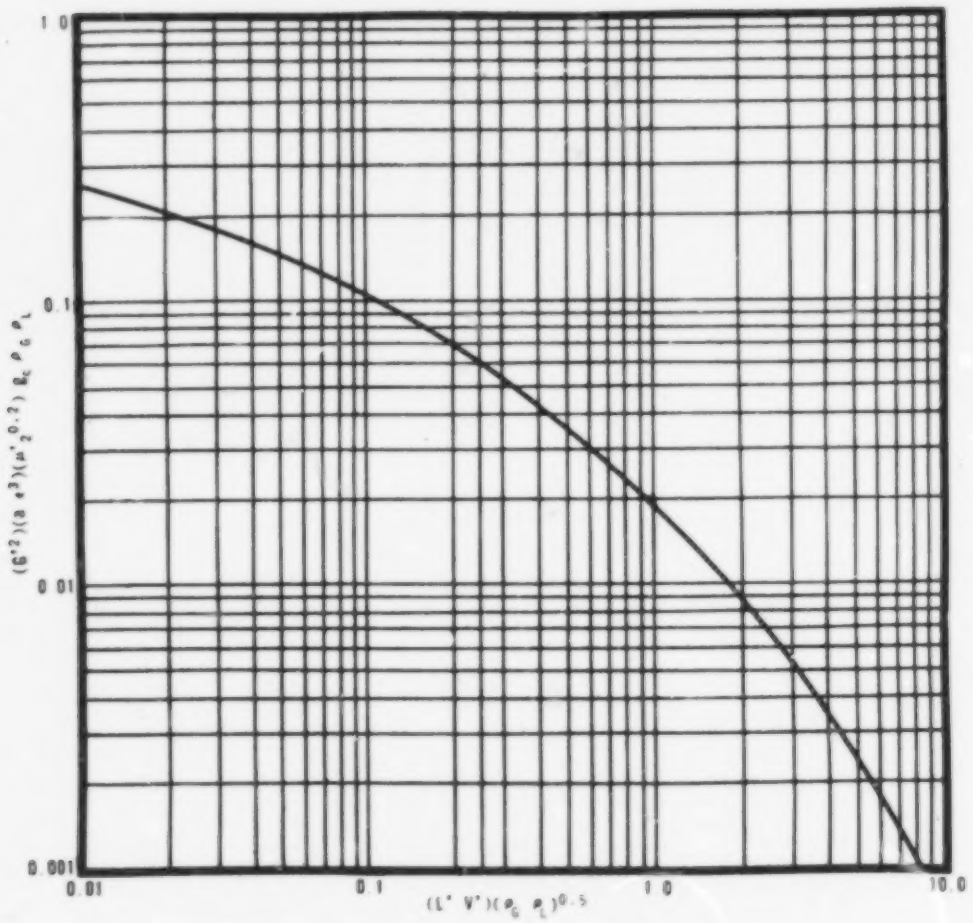


Figure 145. Correlation for flooding rate in randomly packed towers (Lobo, 1945, p. 693).

be used to determine flow rates that will cause flooding. This curve is based on measurements with several liquids and gases on a variety of packings.

For many years packed towers were designed on the same basis as plate or tray towers. The number of theoretical plates or trays required for a given degree of separation was calculated and this quantity multiplied by a figure called height equivalent to a theoretical plate (HETP). This HETP was an experimentally determined figure varying widely with packing, flow rates of each fluid used, and concentration of solute for any specific system. Experimental evaluation of these variables made use of this system too cumbersome and it is now rarely used. Design procedures now employ the concept of the transfer unit. The major design items to be calculated are the column diameter, number of transfer units, the height of a transfer unit, and the system pressure drop. These will be discussed individually.

Tower Diameter

As mentioned previously, gas velocity is limited by flooding conditions in the tower. By use of the design gas volume, design solvent flow rate, and type of packing, the tower diameter can be computed by using Lobo's correlation in Figure 145. Packing factors are obtained from Figure 146. The procedure is as follows:

1. Calculate the factor $\frac{L'}{V'}\left(\frac{\rho_G}{\rho_L}\right)^{0.5}$

   where

   L' = liquid flow rate, lb/hr

   V' = gas flow rate, lb/hr

   ρ_G = gas density, lb/ft^3

   ρ_L = liquid density, lb/ft^3

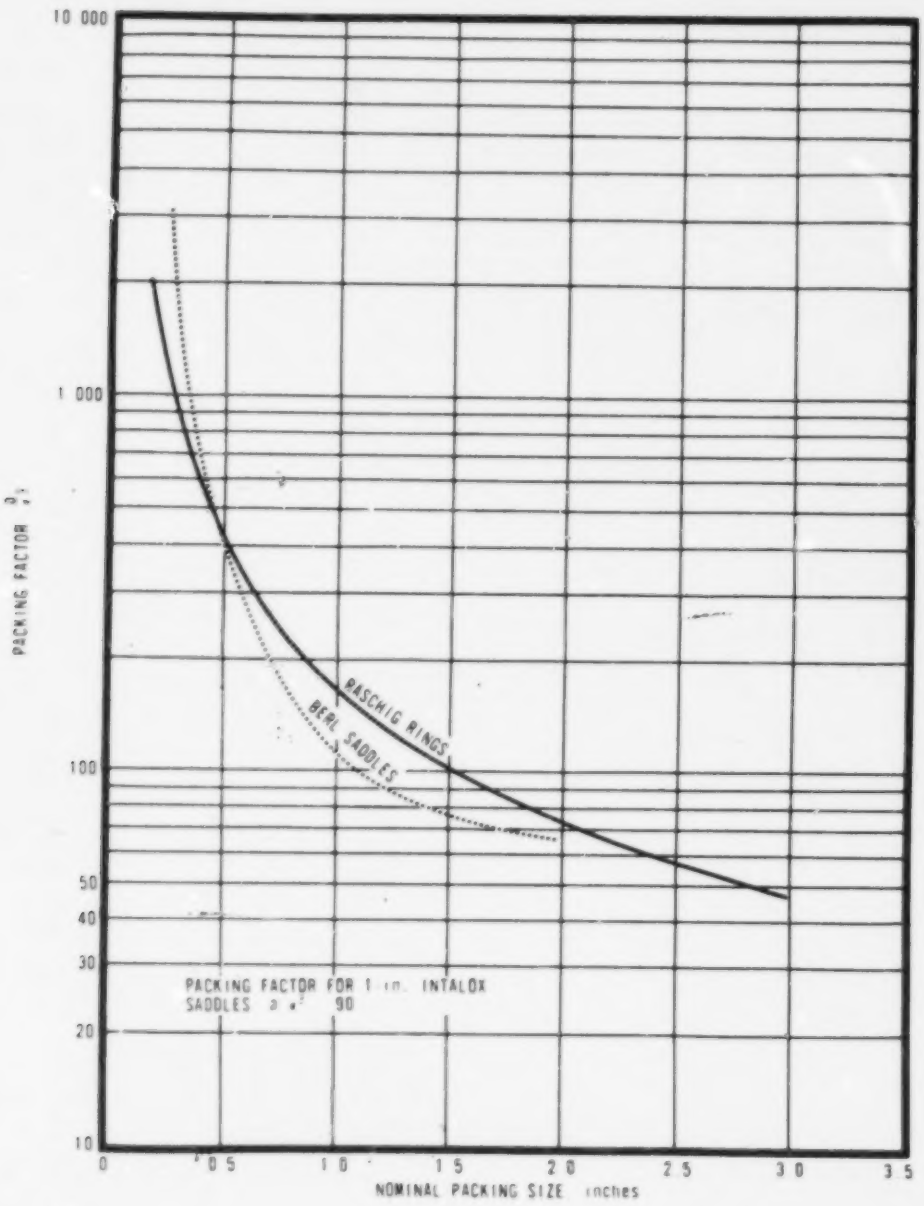


Figure 146. Packing factors for Raschig rings and saddles (Lobo, 1945, p. 693).

2. Using the calculated value in (1), obtain from Figure 145 the value of

$$\frac{\left(G'^2\right)\left(\frac{a}{\epsilon^3}\right)\left(\mu_2'^{0.2}\right)}{g_c\,\rho_G\,\rho_L}$$ where

G' = gas flow rate, lb/sec-ft^2 of tower cross-section

$\frac{a}{\epsilon^3}$ = packing factor from Figure 146.

ρ_G = gas density, lb/ft^3

ρ_L = liquid density, lb/ft^3

μ_2' = liquid viscosity, centipoises

g_c = gravitational constant, 32.2 ft/sec^2.

3. Solve for G', the superficial mass gas velocity at flood point from the factor determined in (2).

4. Calculate S, the tower cross-section area in ft^2 for fraction of flooding velocity selected, f, by the equation

$$S = \frac{V'}{(G')(f)(3,600)} \qquad (92)$$

5. Calculate the tower's inside diameter, Dc, by the equation

$$Dc = \left(\frac{S\,(4)}{\pi}\right)^{0.5} \qquad (93)$$

Tower diameter should be calculated for conditions at both top and bottom of the tower. The tower is designed to the larger diameter.

Number of Transfer Units (NTU)

A transfer unit is a measure of the difficulty of the mass transfer operation and is a function of the solubility and concentrations of the solute gas in the gas and liquid streams. It is expressed as N_{OG} or N_{OL}, depending upon whether the gas film or liquid film resistance controls the absorption rate. The gas film resistance usually controls when solubility of solute in solvent is high and conversely, the liquid film controls when the solubility is low.

In air pollution control work where, in general, a relatively small concentration of solute is to be removed from an airstream, a solvent in which the solute gas is highly soluble is usually selected in order to obtain the highest possible economic separation. Thus, for the majority of cases encountered, the gas film resistance will be controlling.

One of the most widely used methods of determining the number of transfer units is that proposed by Baker (1935), which is based upon an operating diagram consisting of an equilibrium curve and an operating line. For a given gas-liquid system, if the temperature is constant and the gas partial pressure is varied, the gas concentration in the liquid changes to an equilibrium concentration at each partial pressure. If the system consists of a soluble gas to be removed, an insoluble carrier gas, and a solvent, then, as the amount of soluble gas in the system increases, the equilibrium concentration of the soluble gas in the liquid increases but not proportionally.

These equilibrium conditions can exist for an infinite number of concentration states and, when plotted on X-Y coordinates, become the equilibrium curve. The operating line represents the concentrations of solute in the gas stream and in the liquid phase at various points in the tower. When plotted as moles solute per mole solvent versus moles solute per mole gas on X-Y coordinates, the result is a straight line. Thus, when the composition of the inlet gas and the desired or required degree of absorption are known, the points on the operating line for each end of the column can be calculated. The operating line is the straight line connecting the two points. For absorption to occur, the operating line must lie above the equilibrium curve on the diagram. The relative position of the operating line and equilibrium curve indicates how far the tower conditions are from equilibrium. The more widely separated the lines, the further the tower conditions are from equilibrium and the greater is the driving force for the absorption operation.

Figure 147 illustrates the graphical method of determining the number of transfer units for a countercurrent packed tower with the gas film controlling the absorption rate. The equilibrium curve (line AB) for the particular gas-liquid system is plotted from experimental data, which, for most common systems, has been determined. Much of these data can be located in the International Critical Tables and in Perry (1950). The operating line is a straight line drawn between points D and C. D is the point representing the concentrations of solute in the gas stream and in the liquid stream at the gas inlet and liquid outlet (bottom of the tower). Point C corresponds to these concentrations at the top of the column. Line EF is drawn so that all points on the line are located midway on a vertical line between the operating line and equilibrium curve. Starting at point C on the operating line (conditions at the top of the column), draw a horizontal line CH so that CG = GH. Then draw a vertical line HJ back to the operating line.

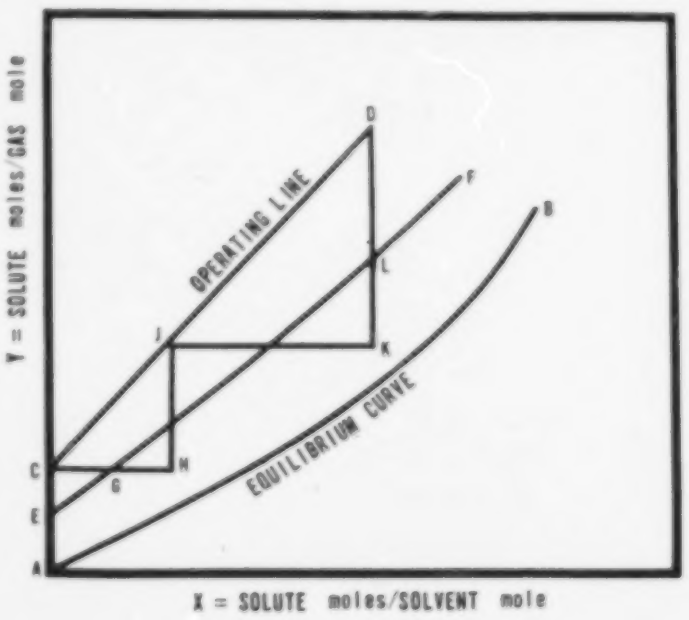


Figure 147. Graphical determination of the number of transfer units.

The step CHJ represents one gas transfer unit. This stepwise procedure is continued to the end of the operating line (conditions at the bottom of the column). Two gas transfer units (N_{OG}) are shown in Figure 147.

If the liquid film resistance is the controlling factor in the transfer of solute to solvent, draw the line EF so that all points on the line are located midway on the horizontal axis between the operating line and equilibrium curve. Then, starting at point D on the operating line, draw a vertical line DK so that DL = LK. The step is completed by drawing a line KJ back to the operating line. This procedure is then continued to point C on the operating line. Figure 147 does not accurately indicate the number of liquid transfer units since the line EF was drawn for the case where the gas film resistance controls.

Height of a Transfer Unit

Generalized correlations are available for computing the height of a transfer unit and are expressed as H_G and H_L for heights of gas and liquid transfer units respectively. These use experimentally derived factors based on the type of packing and the gas and liquid flow rates as shown in equations 94 and 95.

$$H_G = \frac{\alpha G^{\beta}}{L^{\gamma}} \left(\frac{\mu_G}{\rho_G D_G} \right)^{0.5} \qquad (94)$$

where

H_G = height of a gas transfer unit, ft

G = superficial gas rate, lb/hr-ft^2

L = superficial liquid rate, lb/hr-ft^2

α = a packing constant from Table 58

β = a packing constant from Table 58

γ = a packing constant from Table 58

μ_G = gas viscosity, lb/hr-ft

ρ_G = gas density, lb/ft^3

D_G = gas diffusivity, ft^2/hr.

The group $\left(\frac{\mu_G}{\rho_G D_G} \right)$ is known as the Schmidt number as shown in Table 59.

Table 58. CONSTANTS FOR USE IN DETERMINING GAS FILM'S HEIGHT OF TRANSFER UNITS (Treybal, 1955, p. 239)

Packing	α	β	γ	Range of G'	Range of L'
Raschig rings					
3/8 in.	2.32	0.45	0.47	200 to 500	500 to 1,500
1 in.	7.00	0.39	0.58	200 to 800	400 to 500
	6.41	0.32	0.51	200 to 600	500 to 4,500
1-1/2 in.	17.30	0.38	0.66	200 to 700	500 to 1,500
	2.58	0.38	0.40	200 to 700	1,500 to 4,500
2 in.	3.82	0.41	0.45	200 to 800	500 to 4,500
Berl saddles					
1/2 in.	32.40	0.30	0.74	200 to 700	500 to 1,500
	0.81	0.30	0.24	200 to 700	1,500 to 4,500
1 in.	1.97	0.36	0.40	200 to 800	400 to 4,500
1-1/2 in.	5.05	0.32	0.45	200 to 1,000	400 to 4,500
3-in. partition rings	650	0.58	1.06	150 to 900	3,000 to 10,000
Spiral rings (stacked staggered)					
3-in. single spiral	2.38	0.35	0.29	130 to 700	3,000 to 10,000
3-in. triple spiral	15.60	0.38	0.60	200 to 1,000	500 to 3,000
Drip-point grids					
No. 6146	3.91	0.37	0.39	130 to 1,000	3,000 to 6,500
No. 6295	4.56	0.17	0.27	100 to 1,000	2,000 to 11,500

Table 59. DIFFUSION COEFFICIENTS OF GASES AND VAPORS IN AIR AT 25°C AND 1 ATM (Perry, 1950)

Substance	D, cm^2/sec	$\frac{\mu}{\rho D}$
Ammonia	0.236	0.66
Carbon dioxide	0.164	0.94
Hydrogen	0.410	0.22
Oxygen	0.206	0.75
Water	0.256	0.60
Carbon disulfide	0.107	1.45
Ethyl ether	0.093	1.66
Methanol	0.159	0.97
Ethyl alcohol	0.119	1.30
Propyl alcohol	0.100	1.55
Butyl alcohol	0.090	1.72
Amyl alcohol	0.070	2.21
Hyxyl alcohol	0.059	2.60
Formic acid	0.159	0.97
Acetic acid	0.133	1.16
Propionic acid	0.099	1.56
i-Butyric acid	0.081	1.91
Valeric acid	0.067	2.31
i-Caproic acid	0.060	2.58
Diethyl amine	0.105	1.47
Butyl amine	0.101	1.53
Aniline	0.072	2.14
Chloro benzene	0.073	2.12
Chloro toluene	0.065	2.38
Propyl bromide	0.105	1.47
Propyl iodide	0.096	1.61
Benzene	0.088	1.76
Toluene	0.084	1.84
Ethyl benzene	0.077	2.01
Propyl benzene	0.059	2.62
Diphenyl	0.068	2.28
n-Octane	0.060	2.58
Mesitylene	0.067	2.31

$$H_L = \Phi \left(\frac{L}{\mu_L}\right)^{\eta} \left(\frac{\mu_L}{\rho_L D_L}\right)^{0.5} \qquad (95)$$

where

H_L = height of a liquid transfer unit, ft

L = superficial liquid rate, $lb/hr\text{-}ft^2$

μ_L = liquid viscosity, lb/hr-ft

Φ = a packing constant, Table 60

η = a packing constant, Table 60

ρ_L = liquid density, lb/ft^3

D_L = liquid diffusivity, ft^2/hr.

Table 60. CONSTANTS FOR USE IN DETERMINING LIQUID FILM'S HEIGHT OF TRANSFER UNITS (Treybal, 1955, p. 237)

Packing	Φ	η	Range of L'
Raschig rings			
3/8 in.	0.00182	0.46	400 to 15,000
1/2 in.	0.00357	0.35	400 to 15,000
1 in.	0.0100	0.22	400 to 15,000
1-1/2 in.	0.0111	0.22	400 to 15,000
2 in.	0.0125	0.22	400 to 15,000
Berl saddles			
1/2 in.	0.00666	0.28	400 to 15,000
1 in.	0.00588	0.28	400 to 15,000
1-1/2 in.	0.00625	0.28	400 to 15,000
3-in. partition rings	0.0625	0.09	3,000 to 14,000
Spiral rings (stacked staggered)			
3-in. single spiral	0.00909	0.28	400 to 15,000
3-in. triple spiral	0.0116	0.28	3,000 to 14,000
Drip-point grids			
No. 6146	0.0154	0.23	3,500 to 30,000
No. 6295	0.00725	0.31	2,500 to 22,000

The group $\left(\frac{\mu_L}{\rho_L D_L}\right)$ is the Schmidt number as shown in Table 61. Each of these empirical equations neglects the effect of the other film's resistance. Actually, however, even in the case of absorbing highly soluble ammonia in water, experimental results have shown that the liquid film resistance is significant. The height of an overall gas transfer unit, H_{OG}, is determined by the following equation, which takes into account the liquid film resistance.

$$H_{OG} = H_G + (m)\left(\frac{G_m}{L_m}\right)(H_L) \qquad (96)$$

where

m = slope of the equilibrium curve

G_m = gas rate, lb-moles/hr

L_m = liquid rate, lb-moles/hr

These equations are widely accepted for design purposes. Another group of equations listed by Leva (1953) include overall gas and liquid transfer coefficients, $K_g a$ and $K_l a$. Still more recently, Cornell et al., (1960) published correlations based on a mass of experimental data reported up to 1957.

Table 61. DIFFUSION COEFFICIENTS IN LIQUIDS AT 20°C (Perry, 1950)

Solute[a]	n x 10^5 (cm^2/sec) x 10^5	$\frac{\mu}{\rho D}$
O_2	1.80	558
CO_2	1.50	570
N_2O	1.51	665
CI_2	1.76	570
Br_2	1.22	824
H_2	5.13	196
N_2	1.64	613
HCl	2.64	381
H_2S	1.41	712
H_2SO_4	1.73	580
HNO_3	2.60	390
Acetylene	1.56	645
Acetic acid	0.88	1,140
Methanol	1.28	785
Ethanol	1.00	1,005
Propanol	0.87	1,150
Butanol	0.77	1,310
Allyl alcohol	0.93	1,080
Phenol	0.84	1,200
Glycerol	0.72	1,400
Pyrogallol	0.70	1,440
Hydroquinone	0.77	1,300
Urea	1.06	946
Resorcinol	0.80	1,260
Urethane	0.92	1,090
Lactose	0.43	2,340
Maltose	0.43	2,340
Glucose	0.60	--
Mannitol	0.58	1,730
Raffinose	0.37	2,720
Sucrose	0.45	2,230
Sodium chloride	1.35	745
Sodium hydroxide	1.51	665
CO_2[b]	3.40	445
Phenol[b]	0.80	1,900
Chloroform[b]	1.23	1,230
Phenol[c]	1.54	479
Chloroform[c]	2.11	350
Acetic acid[c]	1.92	384
Ethylene dichloride[c]	2.45	301

[a]Solvent is water except where indicated.
[b]Solvent is ethanol.
[c]Solvent is benzene.

Pressure Drop Through Packing

Treybal (1955) states that pressure drop data of various investigators varies widely even for the same packing and flow rates. These discrepancies were probably due to differences in packing density. Moreover, not enough work has been done on liquids of high viscosity for proper evaluation, though it is recognized that, at equal mass flow rates, high-viscosity liquids cause greater gas pressure drop than those of low viscosity do.

Leva's empirical relation applies below the load point. This is as follows:

$$\frac{\Delta P}{Z} = m_1 (10^{-8})(10^{nL'/\rho_L}) \frac{G'^2}{\rho_G} \qquad (97)$$

where

P = pressure drop, lb/ft^2

Z = packed height of tower, ft

m_1 = pressure drop constant from Table 62

n = pressure drop constant from Table 62

L' = superficial mass liquid velocity, $lb/hr\text{-}ft^2$

G' = superficial mass gas velocity, $lb/hr\text{-}ft^2$

ρ_L = liquid density, lb/ft^3

ρ_G = gas density, lb/ft^3.

Illustrative Problem

The following example illustrates the preceding principles of packed tower design. Knowing the amount of solute in the gas stream, the total flow rate of the gas stream, the most suitable solvent, an acceptable packing, and the desired degree of absorption, calculate the tower dimensions.

Given:

Design a packed tower to remove 95% of the ammonia from a gaseous mixture of 10% by volume of ammonia and 90% by volume of air. The gas mixture consists of 80 lb-moles/hr at 68°F and 1 atm. Water containing no ammonia is to be used as solvent and the packing will be 1-inch Raschig rings. The tower will be designed to operate at 60% of the flood point, and isothermal conditions at 68°F will be assumed. The water will not be recirculated.

Problem:

Determine water flow rate, tower diameter, packed height, and tower pressure drop.

Table 62. PRESSURE DROP CONSTANTS FOR TOWER PACKING (Treybal, 1955)

Packing	Nominal size, in.	m	n	Range of L', lb/hr-ft^2	Range of P/Z, lb/ft^2-ft
Raschig rings	1/2	139	0.00720	300 to 8,600	0 to 2.6
	3/4	32.90	0.00450	1,800 to 10,800	0 to 2.6
	1	32.10	0.00434	360 to 27,000	0 to 2.6
	1-1/2	12.08	0.00398	720 to 18,000	0 to 2.6
	2	11.13	0.00295	720 to 21,000	0 to 2.6
Berl saddles	1/2	60.40	0.00340	300 to 14,100	0 to 2.6
	3/4	24.10	0.00295	360 to 14,400	0 to 2.6
	1	16.01	0.00295	720 to 78,800	0 to 2.6
	1-1/2	8.01	0.00225	720 to 21,600	0 to 2.6
Intalox saddles	1	12.44	0.00277	2,520 to 14,400	0 to 2.6
	1-1/2	5.66	0.00225	2,520 to 14,400	0 to 2.6
Drip-point grid tiles	No. 6146 Continuous flue	1.045	0.00214	3,000 to 17,000	0 to 0.5
	Cross flue	1.218	0.00227	300 to 17,500	0 to 0.5
	No. 6295 Continuous flue	1.088	0.00224	850 to 12,500	0 to 0.5
	Cross flue	1.435	0.00167	900 to 12,500	0 to 0.5

Solution:

1. Calculate the water rate: :

a. Equilibrium data for the system ammonia-water are as follows:

X	0.0206	0.0310	0.0407	0.0502	0.0735	0.0962
Y	0.0158	0.0240	0.0329	0.0418	0.0660	0.0920

Plot the equilibrium curve as shown in Figure 148:

The curve is straight approximately to the point P, with a slope of about 0.75. Above point P, the slope is variable and higher than 0.75. Use 0.75 as the slope, m, of the equilibrium curve.

b. When the temperature rise of the solvent is negligible, apply the relation

$$\frac{G_m (m)}{L_m} = 0.70$$

where

m = slope of equilibrium curve = 0.75

G_m = gas rate = 80 lb-moles/hr

L_m = liquid rate, lb-moles/hr

$$L_m = \frac{(80)(0.75)}{0.70} = 85.8 \text{ lb-moles/hr}$$

2. From the given gas flow rate, the calculated liquid rate, and the degree of absorption desired (95% of ammonia), tabulate gas and liquid flow rates at both ends of the tower:

	lb-moles/hr	lb/hr	Density, lb/ft^3
Inlet gas (bottom)	80	2,221	0.0720
Outlet gas (top)	72.4	2,092	0.0750
Inlet water (top)	85.8	1,542	62.4
Outlet liquor (bottom)	93.4	1,671	62.4

3. Calculate the tower diameter:

a. Use conditions at top of tower:

$$(1)\quad \left(\frac{L'}{V'}\right)\left(\frac{\rho_G}{\rho_L}\right)^{0.5} = \left(\frac{1,542}{2,092}\right)\left(\frac{0.0750}{62.4}\right)^{0.5} = 0.0256$$

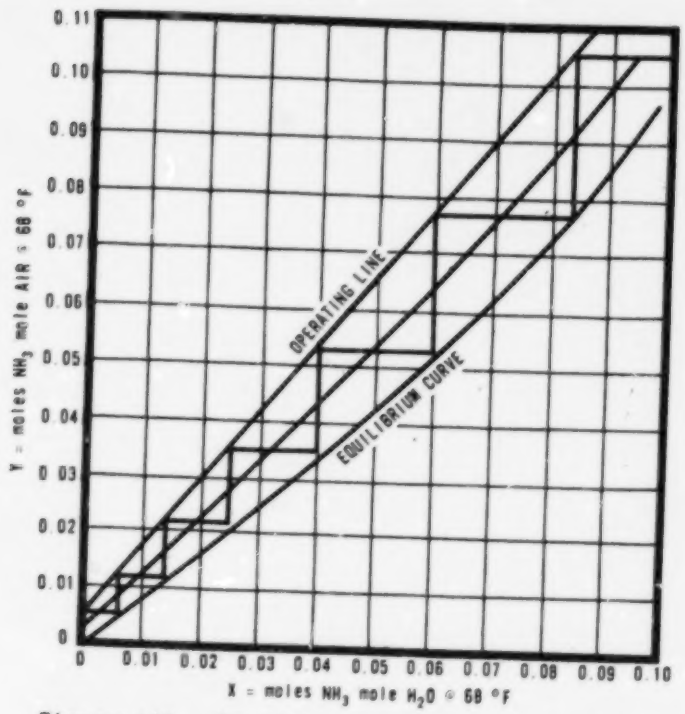

OPERATING LINE
EQUILIBRIUM CURVE
Y = moles NH3 mole AIR @ 68 °F
X = moles NH3 mole H2O @ 68 °F
0 0.01 0.02 0.03 0.04 0.05 0.06 0.07 0.08 0.09 0.10 0.11

Figure 148. Equilibrium curve for ammonia-water system.

(2) From Figure 145, the relationship

$$\frac{(G'^2)\left(\frac{a}{\epsilon^3}\right)(\mu_2)^{0.2}}{(g_c)(\rho_G)(\rho_L)} = 0.19$$

(3) From Figure 146, the packing factor $\left(\frac{a}{\epsilon^3}\right) = 160$

(4) From the relationship in (2), calculate the superficial mass gas velocity (G') at flooding:

$$G' = \left(\frac{(0.19)(32.2)(0.750)(62.4)}{(160)(1)^{0.2}}\right)^{0.5} = 0.424 \text{ lb/sec-ft}^2$$

(5) At 60% of flooding:

$$G'_f = (G')(0.60) = (0.424)(0.60) = 0.254 \text{ lb/sec-ft}^2$$

(6) Tower cross section:

$$S = \frac{2,092 \text{ lb/hr}}{(0.254 \text{ lb/sec-ft}^2)(3,600 \text{ sec/hr})} = 2.29 \text{ ft}^2$$

b. Use conditions at bottom of tower:

(1) $\left(\frac{L'}{V'}\right)\left(\frac{\rho_G}{\rho_L}\right)^{0.5} = \left(\frac{1,671}{2,221}\right)\left(\frac{0.0720}{62.4}\right)^{0.5} = 0.0256$

(2) From Figure 145, the relationship

$$\frac{(G'^2)\left(\frac{a}{\epsilon^3}\right)(\mu_2)^{0.2}}{(gc)(\rho_G)(\rho_L)} = 0.19$$

(3) From Figure 146, the packing factor $\left(\frac{a}{\epsilon^3}\right) = 160$

(4) $G' = \frac{(0.19)(32.2)(0.0720)(62.4)}{(160)(1)^{0.2}} = 0.415 \text{ lb/sec-ft}^2$

(5) $G'_f = 0.415\ (0.60) = 0.249 \text{ lb/sec-ft}^2$

(6) $S = \frac{2,221 \text{ lb/hr}}{(0.249 \text{ lb/sec-ft}^2)(3,600 \text{ sec/hr})} = 2.48 \text{ ft}^2$

c. Select tower with uniform cross-section of 2.48 ft^2

d. Tower diameter:

$$Dc = \left(\frac{(2.48)(4)}{3.14}\right)^{0.5} = 1.78 \text{ ft or } 21.4 \text{ in.}$$

4. Determine the number of transfer units:

a. Calculate mole fractions of solute in gas liquid streams at both ends of the tower.

(1) Bottom of tower:

$$y_1 = \frac{8}{72} = 0.111 \text{ mole } NH_3/\text{mole air}$$

$$X_1 = \frac{7.6}{85.8} = 0.088 \text{ mole } NH_3/\text{mole/air}$$

(2) Top of tower:

$$y_2 = \frac{0.4}{72} = 0.0056 \text{ mole } NH_3/\text{mole air}$$

$X_2 = 0$ (entering water is NH_3 free)

b. Plot the operating line from the data in (a) on the same graph used for the equilibrium curve.

c. By the method of Baker (described previously) graphically determine the number of transfer units:

$$NTU = 6$$

5. Calculate the height of a transfer unit:

a. Gas transfer unit:

$$Hg = \frac{\varphi G^{\beta}}{L^{\gamma}}\left(\frac{\mu_G}{\rho_G D_G}\right)^{0.5}$$

where

$$G = \frac{2,221 \text{ lb/hr}}{2.48 \text{ ft}^2} = 896 \text{ lb/hr-ft}^2$$

$$L = \frac{1,542}{2.48} = 622 \text{ lb/hr-ft}^2$$

φ = 7.00 from Table 58

β = 0.39 from Table 58

γ = 0.58 from Table 58

$\left(\frac{\mu_G}{\rho_G D_G}\right)$ = 0.66 from Table 59

$$H_G = \frac{(7.00)(896)^{0.39}(0.66)^{0.5}}{(622)^{0.58}} = 1.92 \text{ ft}$$

b. Liquid transfer unit:

$$H_L = \Phi\left(\frac{L}{\mu_L}\right)^{\eta}\left(\frac{\mu_L}{\rho_L D_L}\right)^{0.5}$$

where

Φ = 0.01 from Table 60

η = 0.22 from Table 60

L = 622 lb/hr-ft^2

μ_L = 1 centipoise = 2.42 lb/hr-ft

$\left(\frac{\mu_L}{\rho_L D_L}\right)$ = 570 from Table 61

$$H_L = 0.01\left(\frac{622}{2.42}\right)^{0.22}(570)^{0.5} = 0.79 \text{ ft}$$

c. Overall gas transfer unit

$$H_{OG} = H_G + m\left(\frac{G_m}{L_m}\right)(H_L)$$

where

m = slope of equilibrium curve = 0.75

G_m = gas rate = 80 lb-moles/hr

L_m = liquid rate = 85.8 lb-moles/hr

$$H_{OG} = 1.92 + \frac{(0.75)(80)(0.79)}{(85.8)} = 2.47 \text{ ft}$$

6. Calculate the packed tower height (Z):

$$Z = NTU \times H_{OG}$$

$$Z = 6 \times 2.47 = 14.8 \text{ ft}$$

7. Calculate the tower pressure drop

$$\frac{\Delta p}{Z} = m_1(10^{-8})\left(10^{nL/\rho_L}\right)\left(\frac{G^2}{\rho_G}\right)$$

where

Δp = pressure drop, lb/ft^2

Z = packed height = 14.8 ft

m_1 = 32.10 from Table 62

n = 0.00434 from Table 62

L = 622 lb/hr-ft^2

ρ_L = 62.4 lb/ft^3

G = 896 lb/hr-ft^2

ρ_G = Avg gas density = 0.036 lb/ft^3

$$\Delta p = \frac{(32.1 \times 10^{-8})(10)^{(0.00434)(622)/62.4}(896)^2(14.8)}{0.0736}$$

$$\Delta p = 57.2 \text{ lb/ft}^2$$

$$\Delta p = \frac{57.2 \text{ lb/ft}^2 \text{ (1 in. WC)}}{5.197 \text{ lb/ft}^2} = 11.0 \text{ in. WC}$$

PLATE OR TRAY TOWERS

In contrast to packed towers, where gas and solvent are in continuous contact throughout the packed bed, plate towers employ stepwise contact by means of a number of trays or plates that are arranged so that the gas is dispersed through a layer of liquid on each plate. Each plate is more or less a separate stage, and the number of plates required is dependent upon the difficulty of the mass transfer operation and the degree of separation desired.

Types of Plates

The bubble cap plate or tray is most common, and most general references deal primarily with it when discussing plate towers. Other types of plates include perforated trays, Turbogrid trays, and Flexitrays.

A schematic section of a bubble cap tray tower is shown in Figure 149. Each plate is equipped with openings (vapor risers) surmounted with bubble caps. Typical bubble caps are illustrated in Figure 150. The gas rises through the tower and passes through the openings in the plate and through slots in the periphery of the bubble caps, which are submerged in liquid. The liquid enters at the top of the tower, flows across each plate and downward from plate to plate through downspouts.

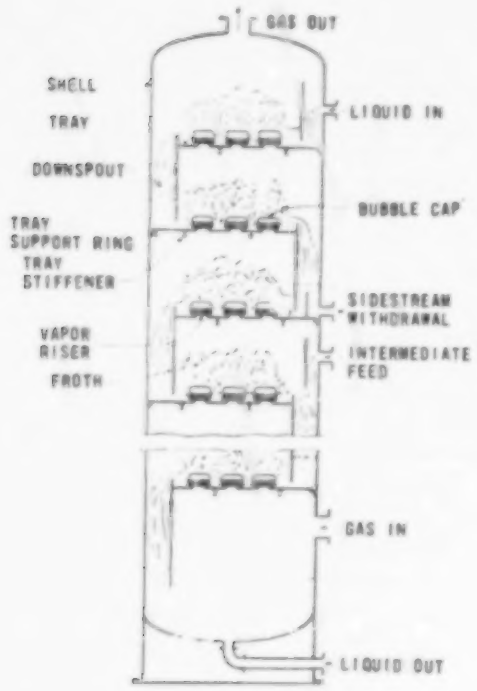


Figure 149. Schematic diagram of a bubble-cap tray tower (Treybal, 1955, p. 111).

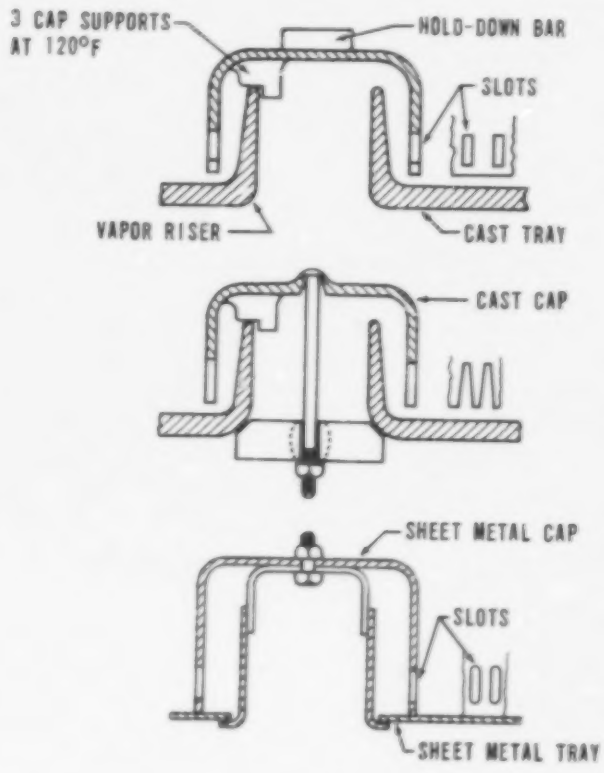


Figure 150. Illustration of some typical bubble caps.

The depth of liquid on the plate, and liquid flow patterns across the plate are controlled by various weir arrangements, which will be discussed in greater detail.

In perforated plates or sieve trays, the gas passes upward through a pattern of holes drilled or punched in the trays. Three-sixteenth-inch-diameter holes spaced on a 3/4-inch triangular pitch are commonly used. A disadvantage of this type is the tendency of liquid to "weep" or leak down through the holes instead of through the downspouts at low gas velocities. Moreover, the trays must be installed perfectly level, or channeling, with resultant loss of efficiency, will occur. On the other hand, a perforated tray costs only 60 to 70 percent as much as a bubble cap plate designed for the same throughput. With towers of the same diameter, perforated trays supposedly have a capacity 10 to 40 percent greater than that of bubble cap plate towers.

With Turbogrid trays, licensed by Shell Development Company, the vapor passes up through the spaces between parallel rods or bars, and the

liquid level on the tray is maintained by the gas pressure beneath the tray. There are no downspouts, and the liquid flows downward through the same openings used by the upward flowing gases. A Turbogrid tray is shown in Figure 151. These are reputed to have high absorption efficiencies even at high capacities with liquids containing a small amount of suspended solids. For example, a 50 percent increase in capacity has been reported where bubble cap plates have been replaced by Turbogrid trays in an existing tower.

Flexitrays, licensed by the Koch Engineering Company, have floating caps that allow variations in the vapor openings with varying gas flow. Different weights can be put on the caps so that the slots will be only partially open at low gas flow rates. This tray also has relatively low resistance to liquid crossflow and supposedly has advantages over bubble cap trays in large columns or operations that require high liquid rates. Flexitrays are claimed to have a capacity 12 to 50 percent higher than that of bubble cap plates and cost only 60 to 80 percent as much.

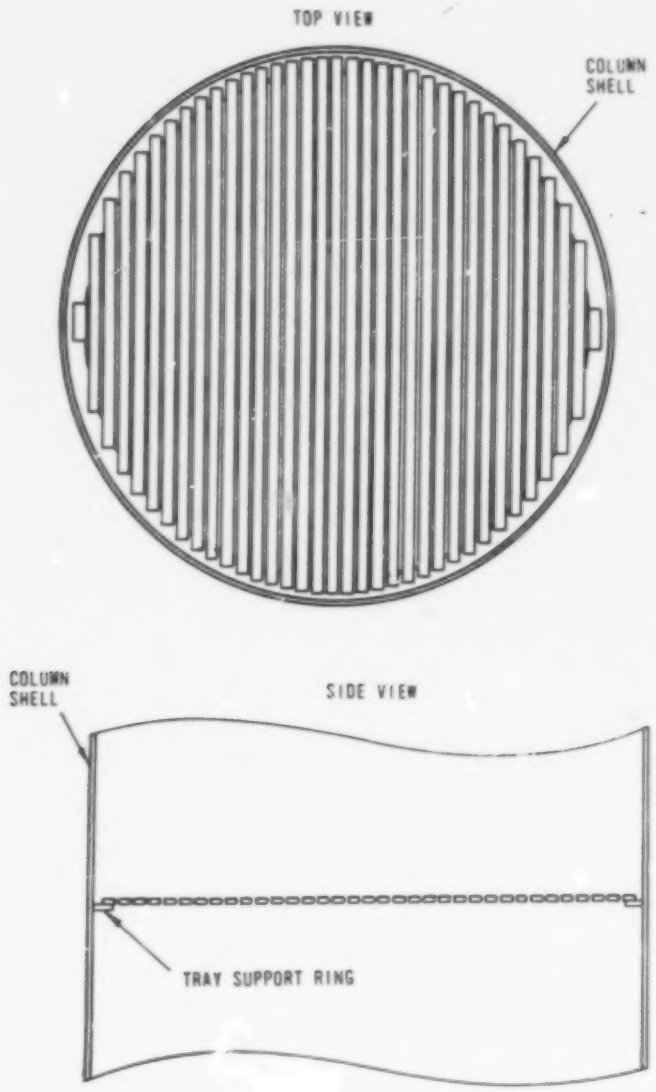


Figure 151. Illustration of a typical Turbogrid tray (Shell Development Co., Emeryville, Calif.).

Although the proponents of the various trays make each sound attractive, it should be remembered that the bubble cap plate is still the standard of the industry and presently outnumbers all the other types. Thus further discussion of plate towers will be devoted exclusively to the design of bubble cap plates.

BUBBLE CAP PLATE TOWER DESIGN

Liquid Flow

Common variations in liquid flow across a bubble cap plate include: (1) Crossflow in opposite directions on alternate plates, (2) crossflow in the same direction on all plates, and (3) split-flow arrangements. There are also variations in weir and downspout design. Several liquid flow patterns are diagrammed in Figure 152, and typical bubble cap tray arrangements for different liquid flow paths are shown in Figure 153.

The single-pass plate with a rectangular weir shown in Figure 153a is the most common. Much of its cross-sectional area is devoted to vapor flow, whereas, a split crossflow plate, shown in Figure 153b, has more of its cross-sectional area devoted to liquid flow. The split-flow tray also has greater downspout area, and the liquid flows a shorter distance from the tray inlet to the overflow weir. Thus split-flow trays handle higher liquid flow rates and are suitable for large-diameter towers.

Cascade tray arrangements, shown in Figures 152d and 153c, are used to keep the liquid level at a more constant depth over the entire tray area despite considerable liquid head differential across the tray. These are used for exceptionally large-diameter towers. Radial flow, Figure 153f, is also a common arrangement in large-diameter towers. The liquid flow may be to and from the center on alternate trays, or it may be in the same direction on all the trays.

Plate Design and Efficiency

For the most efficient operation, bubble cap tray towers must be designed to compromise opposing tendencies. High liquid levels on the trays tend to give comparatively high tray efficiency through long contact time but

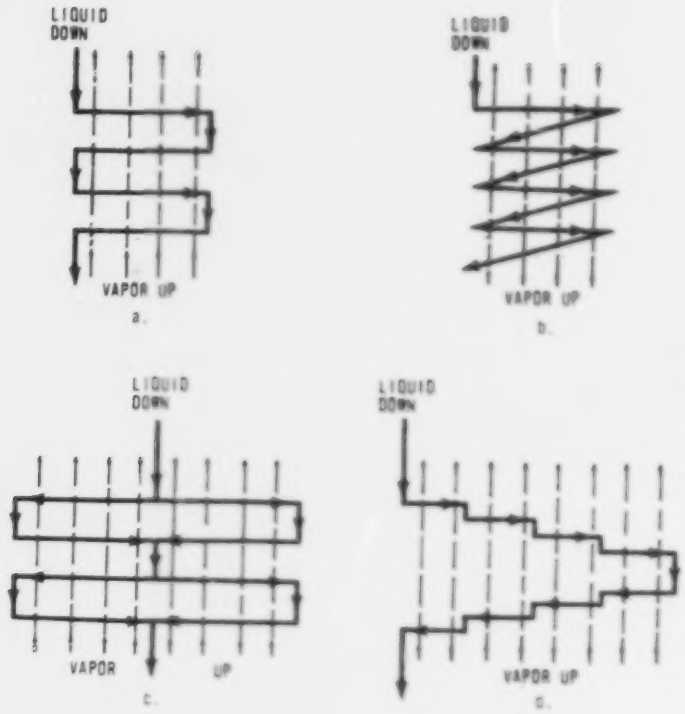


Figure 152. Vapor and liquid flow patterns for bubble cap tray towers: (a) One-pass tray bubble plate column, liquid crossflow, opposite direction on alternate plates; (b) one-pass tray bubble plate column, liquid crossflow, same direction all plates; (c) two-pass tray bubble plate column, split liquid crossflow, opposite directions on alternate plates; (d) one-pass cascade tray bubble plate column, liquid crossflow, opposite direction on alternate plates (Edmister, 1948).

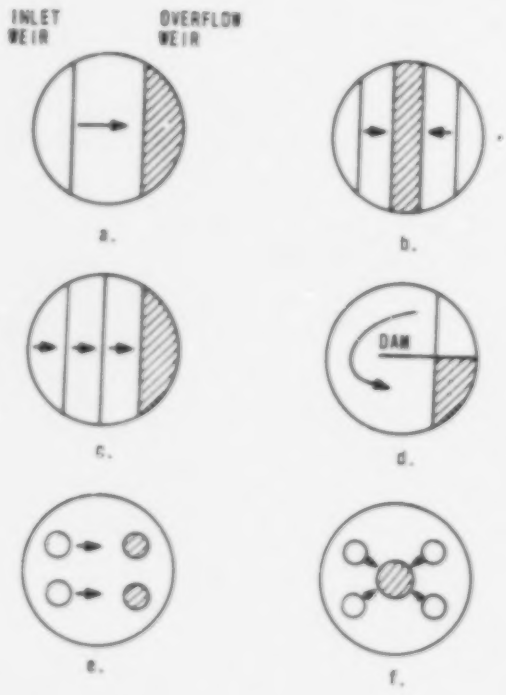


Figure 153. Typical bubble cap tray arrangements: (a) Single crossflow, rectangular weirs; (b) split crossflow, rectangular weirs; (c) cascade crossflow, rectangular weirs; (d) reverse flow, rectangular weir and dividing dam; (e) crossflow, circular weirs; (f) radial flow, circular weirs (Edmister, 1948).

also give high pressure drop per tray. High gas velocity, within limits, gives efficient vapor-liquid contact by creating turbulent conditions but also leads to high pressure drop as well as high liquid entrainment. Treybal (1955) lists recommended conditions and dimensions for bubble cap trays that have been found to be a useful compromise; these are listed in Table 63. In this table, the liquid seal (h_s) is the depth of clear liquid over the top of the bubble cap slots.

As stated before, each tray or plate is a separate stage and, for ultimate efficiency, the gas and liquid would leave each tray in equilibrium with each other at tray conditions. This would be a theoretical plate. This theoretical condition does not normally exist in practice and thus the actual number of trays required to accomplish a specified degree of absorption usually exceeds the number of theoretical units required. The overall plate efficiency of a tower is defined as the number of theoretical equilibrium stages required for a given degree of removal of solute from the gas stream, or concentration of solute in solvent, divided by the actual number of trays required for this same operation. According to Clarke (1947) an overall plate efficiency of 25 percent is a conservative estimate for hydrocarbon absorbers. O'Connell (1946) correlates plate efficiency with gas solubility and liquid viscosity. This correlation is shown in Figure 154. All such correlations are empirically derived, and attempted theoretical methods based on mass-transfer principles do not successfully predict overall plate efficiency.

Flooding

When the liquid capacity of a plate absorber is exceeded, the downspouts become filled. Then, any slight increase in liquid or gas flow increases the liquid level on the trays. A further increase in pressure across the trays causes more liquid to back up through the downspouts, resulting in still higher liquid levels on the trays until, eventually, the tower fills with liquid. This is known as flooding, and at this point, the tray efficiency falls to a very low value, the gas

Table 63. RECOMMENDED CONDITIONS AND DIMENSIONS FOR BUBBLE CAP TRAYS (Treybal, 1955)

Tray spacing	Tower diameter, ft	Tray spacing, in.
	4 or less	6 minimum
	4 or less	18 to 20
	4 to 10	24
	10 to 12	30
	12 to 24	36
Liquid seal	Pressure	Liquid seal, h_s, in.
	Vacuum	0.5
	Atm	1
	500 lb/in^2	3
Liquid flow	a. Not over 0.22 ft^3/sec-ft diameter for single-pass crossflow trays	
	b. Not over 0.35 ft^3/sec-ft weir length for others	
Superficial slot velocity	$3.4/\rho_g$ 0.5 ft/sec minimum $12/\rho_g$ 0.5 ft/sec maximum	
Skirt clearance	0.5 in. minimum; 1.5 in. for dirty liquids	
Cap spacing	1 in. minimum (low slot velocities); 3 in. maximum (high slot velocities)	
Downspout holdup	Minimum of 0.5 sec	
Downspout seal	0.5 in. minimum at no liquid flow	
Weir length	Straight rectangular weirs for crossflow trays, 0.6 to 0.8 of tower diameter	
Liquid gradient	0.5 in. (1 in. maximum)	
Pressure drop per tray	Pressure	Pressure drop
	Atm	0.07 to 0.12 lb/in^2
	300 lb/in^2	0.15 lb/in^2

flow is erratic, and liquid may be forced out the gas exit pipe at the top of the tower. Flooding occurs more rapidly with liquids that tend to froth.

Tower design should allow sufficient downspout area and tray spacing to prevent flooding under anticipated operation variations in both gas and liquid flow. If there is any question, it is better to over-design downspouts since they represent a relatively small-cost item but are important from the standpoint of potential flooding.

Liquid Gradient on Plate

The liquid gradient on a plate is the decreasing liquid depth from the liquid inlet to outlet of the plate due to resistance to fluid flow by the bubble caps and risers. If this gradient is appreciable, more vapor flows through the bubble caps where the liquid depth is least. In extreme conditions the caps near the liquid inlet may become completely inoperative and liquid may flow down through the risers. This is called an unstable plate. Liquid gra-

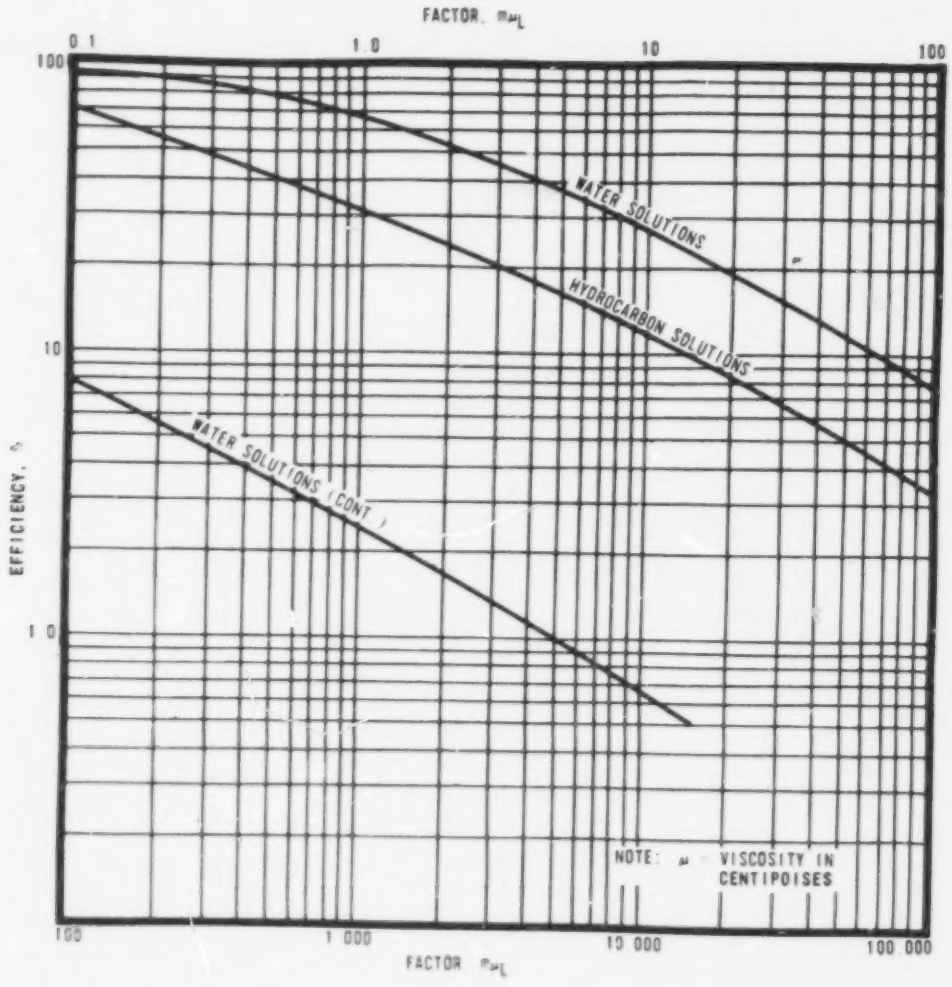


Figure 154. Correlation of plate efficiencies of gas absorbers with gas solubility and liquid viscosity according to method of O'Connell (Sherwood and Pigford, 1952, p. 301).

dient problems would naturally be more likely in large towers, and in these cases, the vapor distribution is controlled by two-pass, split-flow, cascade- or radial-type trays.

Plate Spacing

Operationally, the main consideration regarding tray spacing is to allow sufficient space for the desired liquid level plus space above the liquid for disengagement of the gas and liquid phases without entrainment. Thus, in this respect, tray spacing is closely related to gas velocity through the tower. Spacing should also be sufficient to provide insurance against flooding. If flooding conditions exist even for a short time, a tower with closely spaced trays could become flooded. In actual practice, however, trays are normally spaced for ease in cleaning and maintenance and are not placed close together unless headroom limits the overall tower height. Six inches is usually a minimum, even for very small-diameter towers, and 18 to 24 inches is normally used for towers up to 4 feet in diameter.

Tower Diameter

The superficial linear gas velocity that will usually ensure against excessive entrainment is chosen by the equation

$$V = K \left(\frac{\rho_L - \rho_G}{\rho_G} \right)^{0.5} \qquad (98)$$

where

ρ_L = liquid density, lb/ft^3

ρ_G = gas density, lb/ft^3

K = an empirical constant.

The constant K can be determined by Figure 155, which is based on results of experimental study and good commercial practice. The velocity calculated in equation 98 is valid except for hydrocarbon absorbers, which, according to Perry (1950), should be designed for vapor velocities 65 to 80 percent that of the calculated values. From this calculated velocity, if the volumetric gas flow rate is known, the diameter can easily be determined. In most cases the diameter chosen in this manner is also adequate to handle the normally expected liquid flow rate. Treybal (1955) states that a well-designed single-pass crossflow tray usually handles up to 100 gpm per foot of diameter without excessive liquid gradient.

Number of Theoretical Plates

The number of theoretical plates or trays is usually determined graphically from an operating diagram composed of an operating line and equilibrium curve constructed as previously described in the discussion of packed towers. The actual procedure will be described in the example problem that follows.

If the solute concentrations in the gas and liquid phases are low, as is frequently the case in air pollution control, both the equilibrium and operating curves can be considered as straight lines, and an analytical solution may be used. The relationship as taken from Sherwood and Pigford (1952) is:

$$N_p = \log_e \frac{\left(1 - \frac{mG_m}{L_m}\right)\left(\frac{Y_1 - mx_2}{Y_2 - mx_2}\right) + \left(\frac{m G_m}{L_m}\right)}{\log_e\left(\frac{L_m}{mG_m}\right)} \qquad (99)$$

where

N_p = number of theoretical plates

m = slope of equilibrium curve

G_m = superficial molar mass flow of gas, lb-moles/hr-ft^2 column cross-section

L_m = liquor rate, lb-moles/hr-ft^2 column cross-section

Y_1 = mole fraction of solute in gas stream at concentrated end of countercurrent tower

Y_2 = mole fraction of solute in gas stream at dilute end of countercurrent tower

X_2 = mole fraction of solute in liquid stream at dilute end of countercurrent tower.

Illustrative Problem

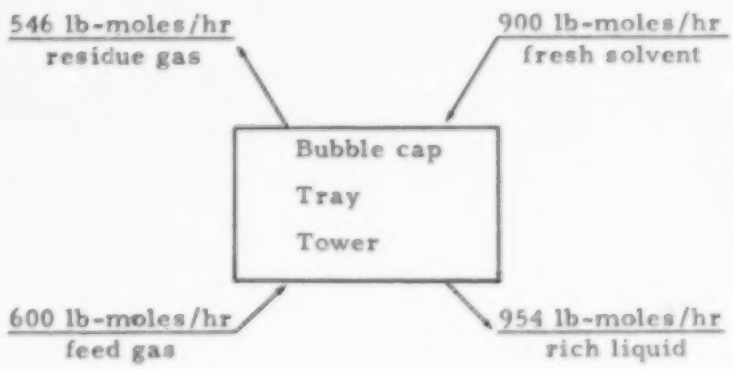
The following example illustrates a method of determining the number of plates or trays required and estimated diameter for a tray tower. No attempt is made to design the bubble cap plate itself for characteristics such as number of caps, cap spacing, slot dimensions, and so forth.

Problem:

Determine the number of actual plates and the diameter of a bubble cap plate tower for removing 90% of the ammonia from a gas stream containing 600 lb-moles/hr of gas at 68°F and 1 atm composed of 10% by volume of ammonia and 90% by volume of air.

Solvent rate expressed as moles solute/mole solvent is obtained from an operating line displaced substantially from the equilibrium curve (Treybal, 1955) as shown in the illustration that follows.

Solvent rate selected is 900 lb-moles/hr of water at 68°F. The tower contains 24-inch tray spacing and 1-inch liquid seal and operates at isothermal conditions.



	Flow, lb-moles/hr	Flow, lb/hr	Density, lb/ft^3
Feed gas	600	16,680	0.0722
Residue gas	546	15,762	0.0750
Absorbent liquid	900	16,200	62.3
Rich liquid	954	17,118	62.3

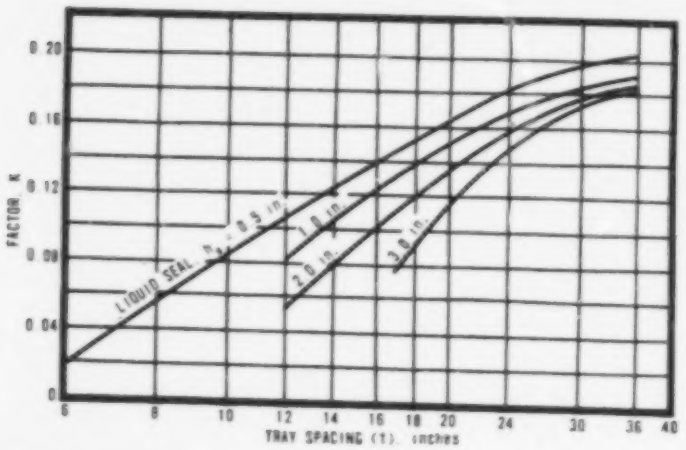


Figure 155. Tray-spacing constants to estimate bubble cap tray tower's superficial vapor velocity (adapted from Perry, 1950).

Solution:

1. Calculate the mole ratios of solute in gas and liquid streams at both ends of the tower:

   (a) Mole ratios at bottom of tower:

$$Y_1 = \frac{60}{540} = 0.111 \text{ mole } NH_3/\text{mole air}$$

$$X_1 = \frac{54}{900} = 0.06 \text{ mole } NH_3/\text{mole } H_2O$$

   (b) Mole ratios at top of tower:

$$Y_2 = \frac{6}{540} = 0.0111 \text{ mole } NH_3/\text{mole air}$$

$$X_2 = 0.0$$

2. The operating line is plotted as shown in Figure 156 from the conditions at top and bottom of the column as determined in step 1. A straight line is drawn between points X_1, Y_1 and X_2, Y_2.

3. The curve of ammonia-water equilibrium is plotted on the same graph from data taken from Leva (1953) in terms of mole ratios.

4. Number of theoretical plates or trays:

   A horizontal line AB is drawn from the operating line at the conditions at the top of the column to the equilibrium curve. Line BC is then drawn vertically from the equilibrium line back to the operating line. The step ABC is a theoretical plate. The stepwise procedure is repeated to the end of the operating line. The solution shows 2.45 theoretical plates.

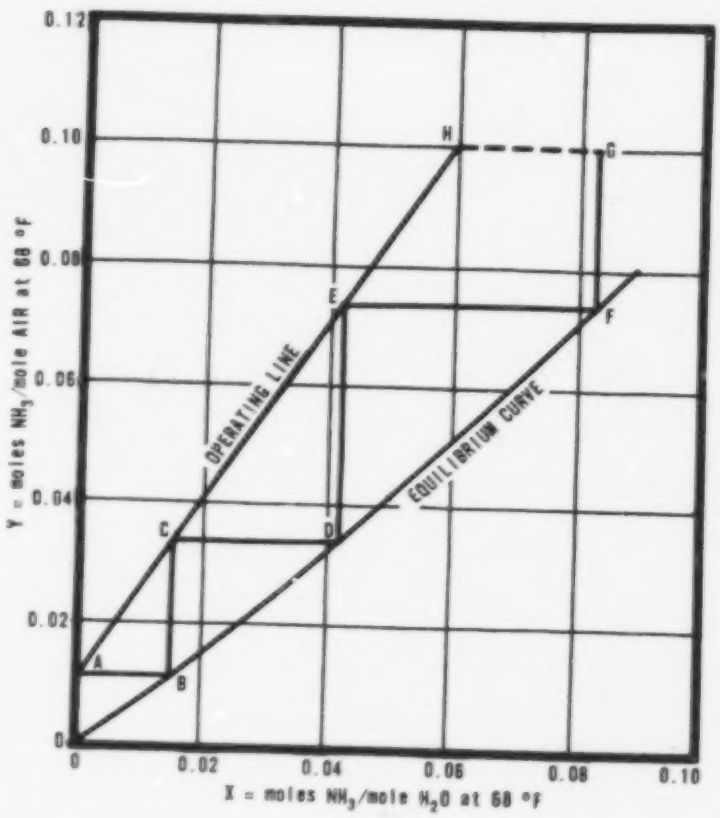


Figure 156. Plot of operating line from the conditions at top and bottom of bubble cap plate tower.

5. Number of actual plates or trays:

   With a viscosity, μ_L, of 1 centipoise for water and a slope of the equilibrium curve, m, of 0.83, (this assumes the equilibrium curve to be straight over the area covered by the operating line), the value $m\mu_L$ is (1)(0.83) = 0.83. From Figure 155, the overall plate efficiency is 72%.

   Actual plates required:

$$\frac{2.45}{0.72} = 3.4 \text{ - use 4 bubble cap trays.}$$

6. Tower diameter:

   From Figure 157, with a 24-inch tray spacing and 1-inch liquid seal, K = 0.17

   (a) Superficial linear gas velocity at bottom of tower:

$$V = 0.17\left(\frac{62.3 - 0.0722}{0.0722}\right)^{1/2} = 5.00 \text{ ft/sec}$$

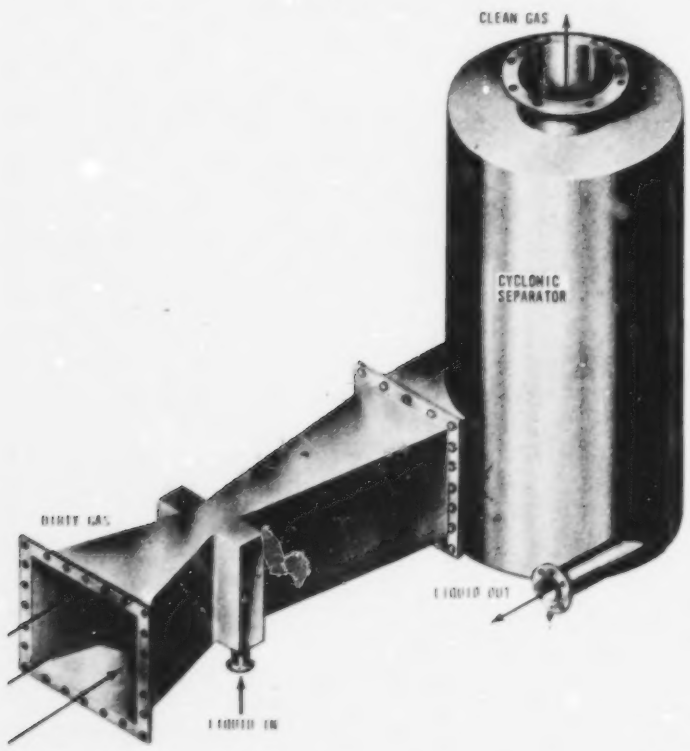


Figure 157. Venturi scrubber or absorber with cyclone-type liquid separator (Chemical Construction Corp., New York, N.Y.).

(b) Volumetric flow rate at bottom of tower:

$$\frac{(600)(379)(528)}{(3,600)(520)} = 64.00 \text{ ft}^3/\text{sec}$$

(c) Tower cross-sectional area:

$$= \frac{64.00}{5.00} = 12.80 \text{ ft}^2$$

(d) Tower diameter:

$$D = \left(\frac{(4)(12.80)}{3.14}\right)^{0.5} = 4.04 \text{ ft.}$$

The principles just discussed are for absorption of a single component. Multicomponent absorption is of great industrial importance in the natural gasoline, petroleum, and petrochemical industries. Absorption of single components such as H_2S from multicomponent gases will be discussed in Chapter 11. When emissions consist of mixed-solvent vapors, control by adsorption or incineration would probably be more economical than by absorption. Design procedures for multicomponent absorption are more complicated than those described previously and will not be attempted here. Sherwood and Pigford (1952) devote an entire chapter to these procedures.

COMPARISON OF PACKED AND PLATE TOWERS

While devices such as agitated vessels, spray chambers, and venturi absorbers have limited application for gas absorption, the choice of equipment is usually between a packed tower and a plate tower. Both devices have advantages and disadvantages for a given operation, depending upon many factors, such as flow rates for both gas and liquid, and degree of corrosiveness of the streams. Final selection should be based upon the following comparative information:

1. Packed towers are less expensive than plate towers where materials of construction must be corrosion resistant. This is generally true for towers less than 2 feet in diameter.

2. Packed towers have smaller pressure drops than plate towers designed for the same throughput and, thus, are more suitable for vacuum operation.

3. Packed towers are preferred for foamy liquids.

4. The liquid holdup is usually less in a packed tower.

5. Plate towers are preferable where the liquid contains suspended solids since they can be more easily cleaned. Packed towers tend to plug more readily.

6. Plate towers are selected in larger sizes, to minimize channeling and reduce weight. Channeling is corrected in the larger diameter and tall packed towers by installation of redistributor trays at given intervals.

7. Plate towers are more suitable where the operation involves appreciable temperature variation since expansion and contraction due to temperature change may crush the packing in the tower.

8. In operations where there is heat of solution that must be removed, plate towers are superior in performance since cooling coils can be easily installed on the plates.

9. Most conditions being equal, economic considerations favor packed towers for sizes up to 2 feet in diameter.

VESSELS FOR DISPERSION OF GAS IN LIQUID

Probably the simplest method of dispersing a gas in a liquid for absorption is by injecting the gas through a perforated pipe or sparger of some type into a vessel filled with the liquid. Unless the sparger has minute perforations, the gas bubbles formed tend to be too large and thus present a relatively small interfacial surface for the absorption operation. If the sparger is designed to create the necessary small bubbles, power requirements to force the gas through the small openings are high.

Increased dispersion may also be achieved by injecting the gas just below a rotating propeller, where the shearing action of the blade breaks up the large bubbles. With a single vessel, the advantage of true countercurrent flow cannot be fully realized since, if there is good agitation, the concentration of absorbed gas in the liquid is uniform throughout the vessel. Thus, absorption equivalent to only one theoretical plate can be achieved per vessel. Although absorption with this equipment is usually batchwise, continuous operation can be obtained with a series of vessels wherein the gas and liquid pass from vessel to vessel in opposite directions.

Vessels such as these have been used to remove highly odorous gaseous products from the reaction of sulfur and sperm oil in the manufacture of specialty lubricants. Here the effluent gases, containing a considerable percentage of hydrogen sulfide, are forced by their own pressure from the closed reactor, through a vent pipe fitted with a sparger, into a tank filled with caustic soda. This arrangement, without auxiliary mechanical agitation of the liquid, reduces the odor of the effluent gas to an innocuous level. Control, however, is effected primarily by chemical reaction rather than by true absorption.

Small tanks containing water or caustic soda are used to eliminate visible emissions from vents of hydrochloric acid storage tanks during tank loading. Without any control device, these emissions of hydrogen chloride vapor are dense enough to violate most air pollution ordinances regarding opacity. The opacity can be reduced to a negligible amount by bubbling the displaced tank vapors through a simple perforated pipe into the water or caustic soda.

SPRAY TOWERS AND SPRAY CHAMBERS

Interphase contact in spray-type absorbers is achieved by dispensing the liquid in the form of a spray and passing the gas through this spray. In order to present a large liquid surface available for contact, sprays of droplets ranging in size from 500 to 1,000 microns are necessary. Fine droplets require, however, high pressure drop across the spray nozzles, and there is danger of liquid entrainment at all except very low gas velocities.

In a simple countercurrent spray tower where the liquid is sprayed down from the top and the gas passes upward through the spray, absorption equivalent to one transfer unit is about all that can be expected. Unless the diameter-to-length ratio is very small, the gas will be well mixed with the spray, and true countercurrent flow will not be realized. Higher gas velocities without excessive entrainment can be obtained with a centrifugal-type spray chamber, whereby the spray droplets are forced to the chamber walls by the centrifugal action of tangentially entering gas before they can be carried out the top of the chamber. With this arrangement, there is a crossflow type of contact, and the degree of contact is limited to about one theoretical plate or transfer unit.

Spray chambers or towers have been used extensively for control of particulate matter but, according to Sherwood and Pigford (1952), their use for pure gas absorption seems to be limited to air conditioning or deaeration of water where very few transfer units are required. These chambers may also be used for some highly soluble gases when the degree of required removal is small, but, in air pollution control work, this type of operation is not common. They have been used as precleaners for particulate removal from gas streams where other devices are used for ultimate control of air pollution.

VENTURI ABSORBERS

Like spray towers and spray chambers, equipment using the venturi principle is primarily used for removing particulates from gas streams, though it has some application to gas absorption. In gas absorbers, the necessary interphase contact is obtained by differences between the velocity of gas and liquid particles, and by turbulence created in the venturi throat. Dispersion in venturi devices is achieved in two ways: By injecting the liquid into the gas stream as it passes through the venturi, as shown in Figure 157, or by admitting the gas to the liquid stream

as it passes through the venturi, as shown in Figure 158. In the latter case, the venturi is also a vacuum-producing device and inspirates the gas into the venturi throat. With both types, a gas-liquid separation chamber is necessary to prevent entrainment. This can be a simple tank, the stream from the venturi tube impinging on the liquid surface, or, more efficiently, a cyclone-type separator.

For the unit shown in Figure 157, the gas velocities in the venturi throat range from 200 to 300 feet per second, and the liquid is injected into the stream at a rate of about 3 gpm per 1,000 cfm of gas handled. These units are designed specifically for collection of submicron particulate matter, and utilize high horsepower. For the liquid-jet eductor types, the liquid consumption is 50 to 100 gpm per 1,000 cfm of gas handled at a draft of 1 inch of water. The liquid-jet eductor types are capable of developing drafts up to 8 inches of water at higher liquid flow rates. They find application principally for the absorption of soluble gases, but are also used for collection of particulate matter larger than 1 or 2 microns in diameter.

Venturi units obtain a high degree of liquid-gas mixing but have a disadvantage of a relatively short contact time. Various literature sources have indicated a high efficiency of absorption for very soluble gases such as sulfur dioxide and ammonia; however, for oxides of nitrogen where contact time is of atmost importance, Peters (1955) reports efficiencies of absorption of from 1 to 3 percent. Because of the high degree of efficiency of venturi scrubbers for particulate removal, they seem desirable for use with a dirty gas stream that also contains a highly soluble gas that must be removed. A major disadvantage of venturi units is the high pressure drop (often as high as 30 inches of water) with attendant high power requirements for operation.

Figure 158. Venturi liquid-jet eductor-type absorber (Schutte and Koerting Company, Cornwells Heights, Penna.).

NOTATIONS

A	=	surface separating hot and cold media, ft^2
C	=	specific heat, Btu/lb-°F
D	=	outside diameter tube, ft
D_i	=	inside diameter tube, ft
D_v	=	diffusion coefficient, ft^2/hr
f	=	friction factor
g	=	acceleration of gravity, 64.4 ft/sec-sec
G	=	mass velocity of flow, $lb/hr\text{-}ft^2$
G_b	=	mass velocity through baffle opening, $lb/hr\text{-}ft^2$
G_c	=	maximum cross flow velocity, $lb/hr\text{-}ft^2$
G_e	=	weighted mass velocity, $G_c \times G_b$, $lb/hr\text{-}ft^2$
G_i	=	mass velocity inside the tube, $lb/hr\text{-}ft^2$
h	=	coefficient of heat transfer, $Btu/hr\text{-}ft^2\text{-}°F$
k	=	thermal conductivity, $Btu/hr\text{-}ft^2\text{-}°F$
K	=	coefficient of mass transfer, lb moles/ $hr\text{-}ft^2$ atmospheres
L	=	tube length, ft
M_m	=	molecular weight of mixture (vapor plus inert gas)
M_v	=	molecular weight of vapor
P_c	=	partial pressure of vapors at t_c, atm
P_v	=	partial pressure of vapors at t_v, atm
P_{BM}	=	logarithmic mean of the vapor pressures at the interface and at the vapor stream, atm
P	=	total pressure on system, atm
q	=	quantity of heat, Btu/hr
t_c	=	condensate temperature, °F
t_v	=	vapor temperature, °F
t_w	=	water temperature, °F
U_c	=	condensing coefficient for pure vapor between t_c and t_w, $Btu/hr\text{-}ft^2\text{-}°F$
w	=	rate of flow, lb/hr
λ	=	latent heat, Btu/lb
μ	=	viscosity at average temperature, lb/hr-ft
μ_f	=	viscosity at average film temperature, lb/hr-ft
μ_w	=	viscosity at tube wall temperature, lb/hr-ft
ρ	=	density at average fluid temperature, lb/ft^3

CHAPTER 6

METALLURGICAL EQUIPMENT

FURNACE TYPES

JOHN A. DANIELSON, Senior Air Pollution Engineer

STEEL-MANUFACTURING PROCESSES

WILLIAM F. HAMMOND, Senior Air Pollution Engineer
JAMES T. NANCE, Intermediate Air Pollution Engineer
KARL D. LUEDTKE, Intermediate Air Pollution Engineer

IRON CASTING

WILLIAM F. HAMMOND, Senior Air Pollution Engineer
JAMES T. NANCE, Intermediate Air Pollution Engineer

SECONDARY BRASS- AND BRONZE-MELTING PROCESSES

WILLIAM F. HAMMOND, Senior Air Pollution Engineer
JAMES T. NANCE, Intermediate Air Pollution Engineer
EMMET F. SPENCER, Intermediate Air Pollution Engineer*

SECONDARY ALUMINUM-MELTING PROCESSES

WILLIAM F. HAMMOND, Senior Air Pollution Engineer
HERBERT SIMON, Senior Air Pollution Engineer

SECONDARY ZINC-MELTING PROCESSES

GEORGE THOMAS, Intermediate Air Pollution Engineer

LEAD REFINING

JAMES T. NANCE, Intermediate Air Pollution Engineer
KARL D. LUEDTKE, Intermediate Air Pollution Engineer

METAL SEPARATION PROCESSES

JAMES T. NANCE, Intermediate Air Pollution Engineer
EMMET F. SPENCER, Intermediate Air Pollution Engineer*

CORE OVENS

GEORGE THOMAS, Intermediate Air Pollution Engineer

FOUNDRY SAND-HANDLING EQUIPMENT

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

HEAT TREATING SYSTEMS

JULIEN A. VERSSEN, Air Pollution Engineer

*Now with Inorganic Chemical Division, FMC Corporation, Newark, California.

BLANK PAGE

CHAPTER 6

METALLURGICAL EQUIPMENT

Efficient control of air contaminants from metallurgical furnaces has been achieved only in recent years. Since most of these furnaces discharge high-temperature effluents containing submicron-size dusts and fumes, these effluents must sometimes be cooled and often further conditioned before ducting to a control device. The control device must be one capable of high-efficiency collection of submicron particles.

This chapter discusses these control devices and the air pollution problems encountered in steel, iron, brass, aluminum, zinc, lead, and metal separation processes. Processes related to metallurgical operations such as manufacture of sand cores, foundry sand-handling equipment, and heat treating systems will be discussed near the end of this chapter.

For those not acquainted with the many types of melting furnaces, the first part of this chapter describes briefly the more common furnaces and their principles of operation. The air pollution aspects of these furnaces are not discussed immediately since these problems are usually a function of the specific melting process and not of the type of furnace used.

FURNACE TYPES

REVERBERATORY FURNACE

A reverberatory furnace operates by radiating heat from its burner flame, roof, and walls onto the material heated. This type of furnace was developed particularly for melting solids and for refining and heating the resulting liquids. It is generally one of the least expensive methods for melting since the flame and products of combustion come in direct contact with the solid and molten metal. The reverberatory furnace usually consists of a shallow, generally rectangular, refractory hearth for holding the metal charge. The furnace is enclosed by vertical side walls and covered with a low, arched, refractory-lined roof. Combustion of fuel occurs directly above the molten bath; the walls and roof receive radiant heat from the hot combustion products and, in turn, reradiate this heat to the surface of the bath. Transfer of heat is accomplished almost entirely by radiation.

Reverberatory furnaces are available in many types and designs, depending upon specific job requirements. Probably the largest of the reverberatory furnaces is the open-hearth furnace, widely used in the manufacture of steel. This furnace operates in conjunction with two heat regenerators consisting of brick checkerwork; these remove the heat from the effluent and transfer it to the incoming air (Figure 159). The transfer is accomplished by a system of butterfly valves, which allows the furnace gases to pass through one set of checkerwork, giving up heat, while the incoming combustion air passes through the second set of checkerwork, taking up heat. Periodically the valves are reversed, which allows incoming combustion air to preheat in the first set of checkerwork while the furnace gases are heating the second regenerator. The charge is introduced through refractory-lined doors in the front wall; finished steel and slag are removed through a taphole in the rear wall. Heat is provided by passing a luminous flame with excess air over the charged material. Details of operation in the production of steel with the open-hearth furnace are described later in this chapter.

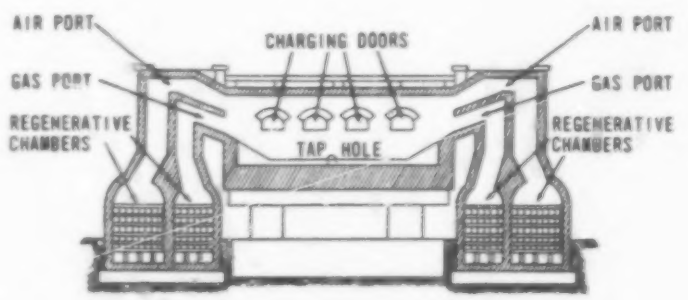


Figure 159. An open-hearth furnace (Begeman, 1947).

Another type of reverberatory furnace is the cylindrical furnace, commonly used in the nonferrous industries for melting and holding small heats of aluminum, brass, and various alloys. Cylindrical reverberatory furnaces are relatively small, usually rated at 500 pounds of aluminum. These furnaces (Figure 160) are fired through two tangential nozzles that promote excellent combustion characteristics and provide very rapid melting. The furnace may be charged through a top opening or through the end door. The end door also serves as an access to the metal bath for adding alloying materials or drossing.

Reverberatory furnace designs often use rotary tilting mechanisms. A tilting furnace promotes ease of metal distribution for all types of casting

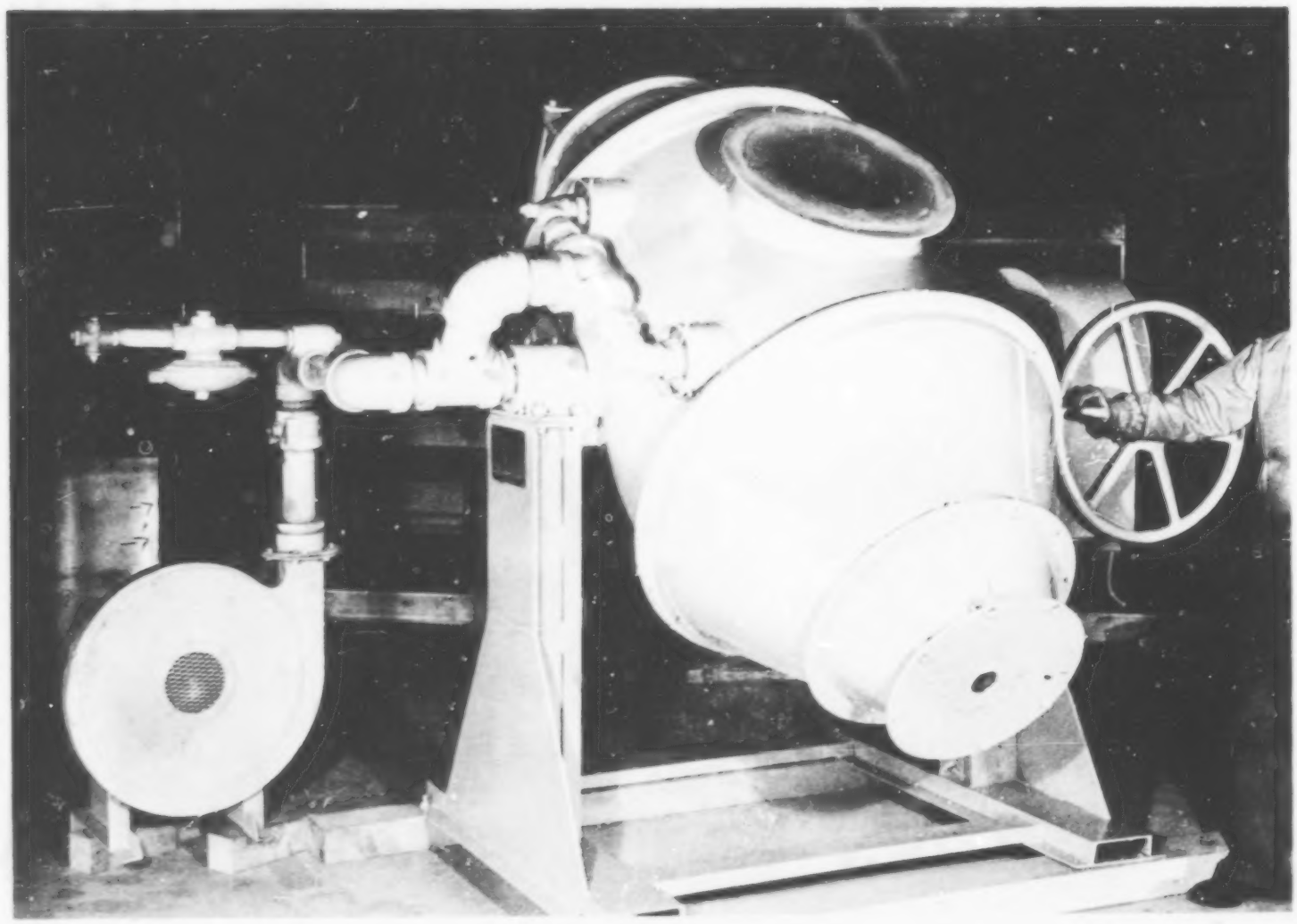


Figure 160. Gas-fired, cylindrical reverberatory furnace (Bulletin No. 6011, Hevi-Duty Heating Equipment Co., Watertown, Wisc.).

operations--permanent mold, die casting, and sand operations. Charging is accomplished by means of a hopper that acts as a stack for the exhaust gases; the metal charge lodges in the lower part of the hopper where the melting takes place. The furnace is end fired, and tilting of the furnace is accomplished by means of an air or hydraulic ram.

Another type of tilting reverberatory furnace (Figure 161) normally finds application in nonferrous metallurgical operations where large heats are required. In this installation, the furnace is gas fired tangentially with three burners.

Many other variations and combinations of furnaces using the reverberatory principle are manufactured by many firms throughout the United States and are available commercially as prefabricated units.

CUPOLA FURNACE

For many years the cupola has been a standard melting furnace for producing gray iron. It is also used to melt or reduce copper, brasses, bronzes, and lead. In addition to its high efficiency, the cupola is simple in its construction and operation. Unless carefully considered, however, its operation may lead to difficulties because of variations in quantity and quality of raw metal, fuel, and air.

The basic equipment for a gray iron-melting operation consists of the cupola (Figure 162), which is essentially a refractory-lined cylinder open at the top and equipped with air ports (known as tuyeres) at the bottom. Air is supplied from a forced-draft blower. Alternate charges of metal, coke, and limestone are placed on top of the burning coke bed to fill the cupola. The heat generated melts the metal, which is drawn off through a tap hole. The two principal dimensions of the cupola are its diameter and operating height (charging door to tuyeres). The diameter determines the melting capacity, and the height affects the thermal efficiency.

Combustion Air

The control of air at the tuyeres influences production rates, costs, metal losses, coke ratios, stack

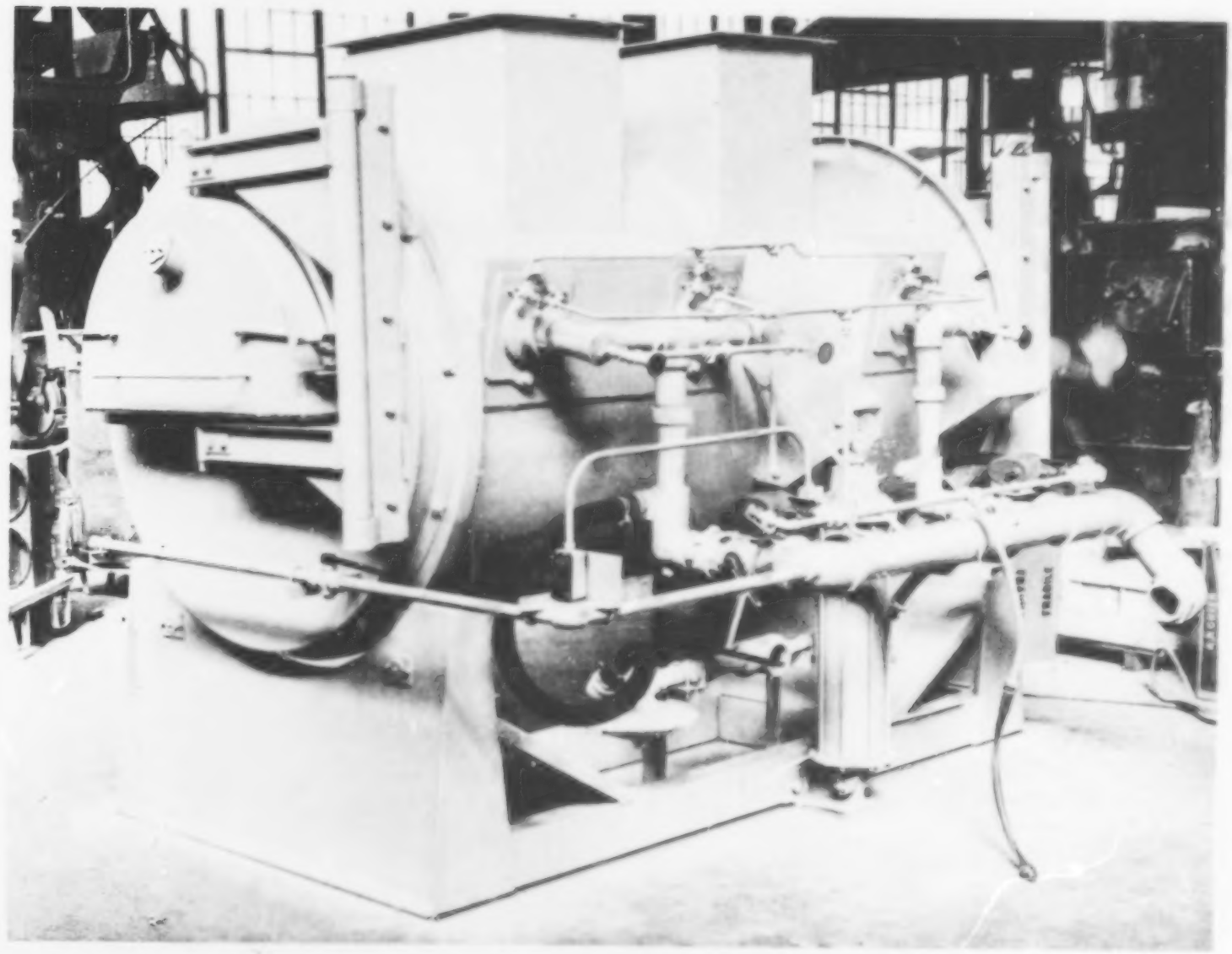


Figure 161. Tangentially fired tilting reverberatory furnace (Bulletin No. 6011, Hevi-Duty Heating Equipment Co., Watertown, Wisc.).

temperature, physical properties of the metal, and volume of stack emissions. Air is required, not only to furnish oxygen for the combustion of coke, which supplies the heat required for melting the iron, but also to aid in the potential combustion of the carbon, silicon, and manganese in the metal. The latter function greatly influences the resultant chemical and physical properties of the metal when it is poured into the mold (Molcohy, 1950).

Combustion air may be provided by a positive-displacement-type blower or a centrifugal blower. The quantity of air theoretically required is determined primarily by the size of the cupola, the melting rate, the metal-coke ratio, and the metal temperature. The actual air supplied may be increased as much as 15 percent to compensate for leakage. Air pressure varies from 8 to 40 ounces per square inch, depending upon design factors such as ductwork layout, tuyere geometry, and the height of the bed through which the air must be forced. Automatic controls are frequently installed to maintain a constant-weight flow of air.

Methods of Charging

Various methods of charging materials into the cupola are used. The smaller cupolas are frequently charged by hand while larger units may be charged with skip hoists with the various types of cars, buckets, cranes, or trolleys. Charging and melting is a continuous operation.

Preheating Combustion Air

In order to increase the efficiency of a cupola, three methods are available for preheating combustion

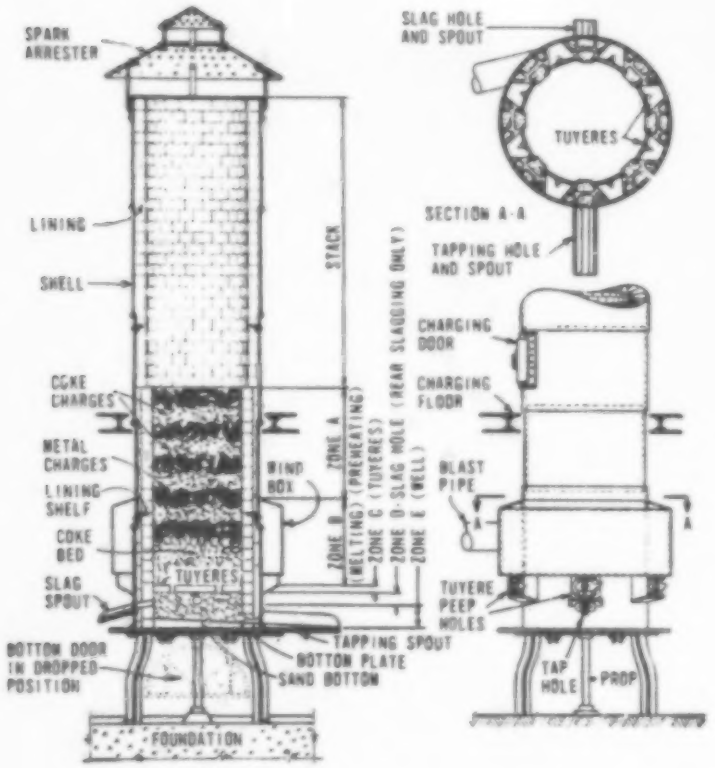


Figure 162. A cupola furnace (American Foundrymen's Association, 1949).

air. In the Moore system, a heat exchanger is used to transfer some of the waste heat of the stack gases to the incoming combustion air. The Whiting system uses a separate external heater for the combustion air. The Griffin system passes the stack gases through a chamber where air is introduced and the CO is burned to CO_2. The gases then pass through a heat exchanger to preheat the combustion air.

ELECTRIC FURNACE

Major advantages of the electric furnace over fuel-fired furnaces are furnace atmosphere control and high-temperature operation. Temperatures as high as 6,000°F are possible for special processes.

The electric furnace has three functions (Porter 1959):

1. Synthesis of compounds not available in the natural state by fusing selected raw materials,
2. purification of ores,
3. alteration of crystalline structure of ores having a satisfactory chemical purity but an undesirable crystal structure.

There are four types of electric furnace: Direct-arc, indirect-arc, resistance, and induction. Each of these types will be discussed briefly.

Direct-Arc Furnace

In the direct-arc furnace, many and varied arrangements are used to heat the metal charge, but radiation between arc and the metal bath is the principal method. Here, the heat is generated by radiation from the arc as well as from the resistance heat effect within the bath, as shown in Figure 163. Graphite and carbon electrodes are usually used and are spaced just below the surface of the slag cover. The current passes from one electrode through the slag, the metal charge, the slag, and back to the other electrode. In some arrangements, the current is carried from the metal charge to the hearth. The slag serves a protective function by shielding the metal charge from vaporized carbon and the extremely high temperatures at the arc.

Indirect-Arc Furnace

In the indirect-arc furnace, the metal charge is placed below the electrodes, and the arc is formed between the electrodes and above the charge (Figure 163). Indirect-arc furnaces are used mainly in the steel industry. One of the common smaller furnaces is the indirect-arc rocking furnace, in which an automatic rocking action of the furnace is employed to ensure a homogeneous melt. This is done by mounting the refractory-lined steel shell on cog bearings so that the furnace may be rocked through a 200° range. Radiated heat from the indirect arc, and conduction from the preheated refractory lining initially melt small scrap, forming a pool of molten metal at the bottom of the furnace. Then the rocking action is initiated, and the molten metal washes against the refractory, picking up additional heat, which is transferred by convection and radiation to the larger pieces of metal. During the heat, the rocking action is advanced gradually to avoid a sudden tumbling of cold metal, which could fracture the graphite electrodes.

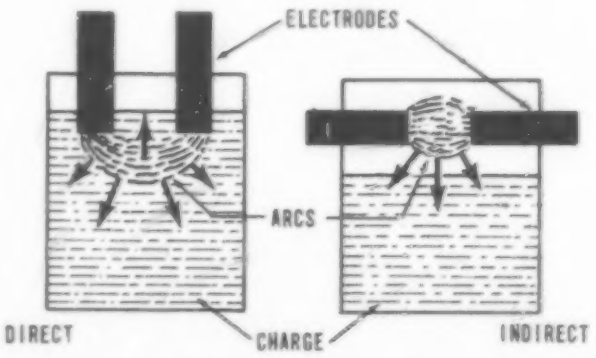


Figure 163. Principles of operation of two types of arc furnaces (Porter, 1959).

Induction Furnace

The induction furnace consists of a crucible within a water-cooled copper coil (Figure 164). An alternating current in the coil around the crucible induces eddy currents in the metal charge and thus develops heat within the mass of the charge. The furnace is used for the production of both ferrous and nonferrous metals and alloys, generally from scrap metal. It provides good furnace atmosphere control and can be used for large-volume production of high-purity materials.

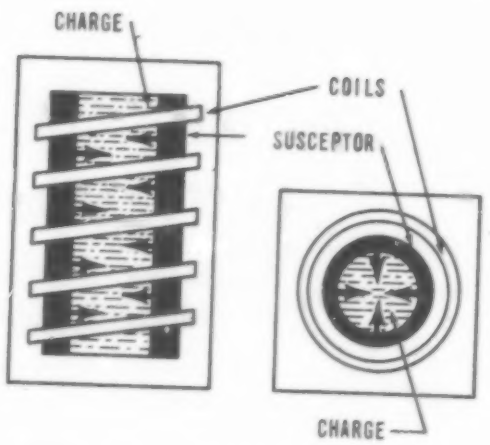


Figure 164. Principles of operation of an induction furnace (Porter, 1959).

Resistance Furnace

Three varieties of resistance furnaces are illustrated in Figure 165. The resistance furnace is essentially a refractory-lined chamber with electrodes, movable or fixed, buried in the charge. It is characterized by its simplicity of design and operation. The charge itself acts as an electrical resistance that generates heat.

The resistance furnace is used in the production of ferroalloys (ferrochrome, ferrosilicon, and others), cyanamide, silicon carbide, and graphite, and in hardening and tempering tools and machine parts.

CRUCIBLE FURNACE

Crucible furnaces, used to melt metals having melting points below 2,500°F are usually constructed with a shell of welded steel lined with refractory materials. Their covers are constructed of materials similar to the inner shell lining and have a small hole over the crucible for charging metal and exhausting the products of combustion. The crucible rests on a pedestal in the center of the furnace and is commonly constructed of a refractory material such as clay-graphite mixtures or silicon carbide. Crucibles are made in several shapes and sizes for melting from 20 to 2,000 pounds, rated in red brass.

Crucible furnaces are classified as tilting, pit, or stationary furnaces. All types are provided with one or more gas or oil burners mounted near the

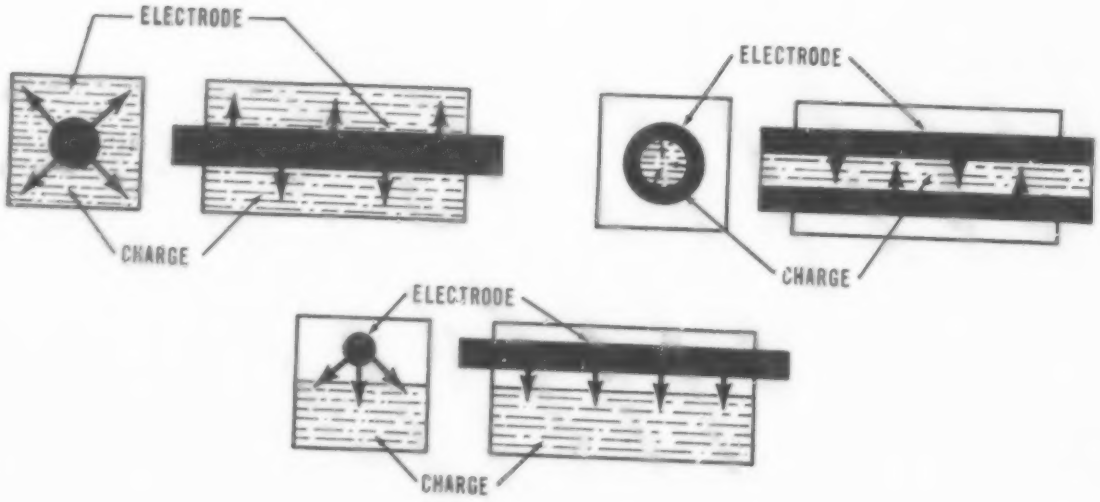


Figure 165. Principles of operation of three types of resistance furnace (Porter, 1959).

bottom of the unit. Flames are directed tangentially around the inside of the furnace. The crucible is heated both by radiation and by contact with the hot gases.

Tilting Furnace

The tilting crucible furnace (Figure 166) is provided with devices for affixing the crucible to the furnace so that the furnace may be tilted with the crucible when the metal is poured. The entire furnace is mounted on trunnions, around which the furnace may be tilted. The tilting mechanism can be operated manually, hydraulically, or electrically.

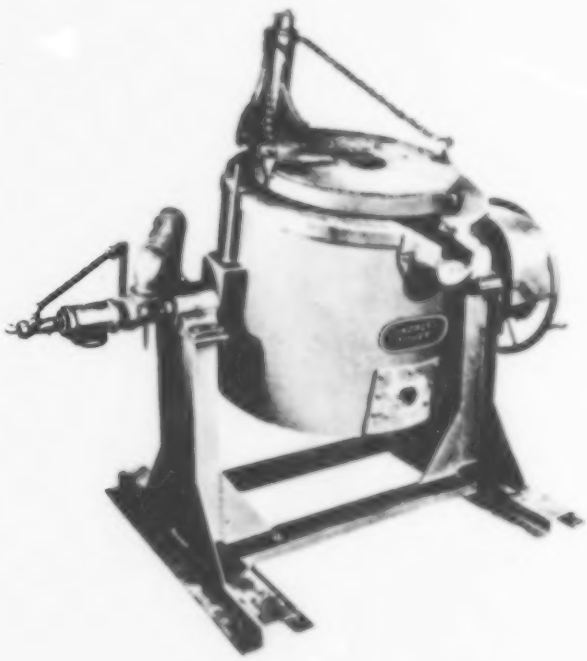


Figure 166. Tilting crucible furnace (Lindberg Engineering Co., Downey, Calif.).

Pit Crucible

The pit crucible furnace derives its name from its location. The top of the furnace is near floor level, which facilitates charging of the metal to the furnace and removing of the crucible for pouring. Pouring is usually accomplished by using the same crucible as a ladle. The furnace cover is provided with rollers or swinging mechanisms for easy removal.

Stationary Crucible

The stationary crucible furnace is almost identical to a pit furnace except that it is not sunk in a pit. These furnaces are commonly used as holding furnaces, and the metal is poured by dipping with hand ladles. Pouring may also be accomplished by removing the crucible and using it as a ladle.

POT FURNACE

Pot furnaces are used to melt metals with melting temperatures below 1,400°F. These furnaces may be cylindrical or rectangular and consist of an outer shell lined with refractory material, a combustion chamber, and a pot. The pots are made of pressed steel, cast steel, or cast iron with flanged tops. The flange rests on the furnace wall, holds the pot above the furnace floor, and seals the contents of the pot from the products of combustion of the fuel used. The shape of the pot depends upon the operation to be conducted. Large rectangular furnaces, generally called kettles, are used to melt large amounts of metal for dipping operations, such as galvanizing. For melting large castings, shallow, large-diameter pots are used. When ingots or other small pieces of metal are to be melted, deep pots are used to promote better heat transfer. Pot furnaces are usually emptied by tilting, dipping, or pumping. A small pot furnace is shown in Figure 167. Combustion equipment ranges from

Figure 167. A gas-fired small pot furnace (Lindberg Engineering Co., Downey, Calif.).

simple atmospheric-type burners located directly below the pot to premix-type burners tangentially fired as in crucible furnaces. The larger kettles are generally provided with many small burners along both sides of the pot.

STEEL-MANUFACTURING PROCESSES

Steel is a crystalline alloy, mainly of iron and carbon, which attains greater hardness when quenched from above its critical temperature than when cooled slowly. Carbon is the most important constituent because of its effect on the strength of the steel and its ability to harden. Other constituents that may be present as impurities or as added alloying elements include manganese, silicon, phosphorus, sulfur, aluminum, nickel, chromium, cobalt, molybdenum, vanadium, and copper (Begeman, 1947).

Steel is made from pig iron and scrap steel by oxidizing the impurities, reducing the iron oxides to iron, and adding the desired alloying constituents. The two common steel-refining processes are: (1) The basic process, wherein oxidation takes place in combination with a strong base such as lime; and (2) the acid process, wherein oxidation takes place without the base addition. The two processes have the common purpose of removing the undesirable elements in the metal by the chemical reaction of oxidation reduction. Depending upon the alloy being produced, the elements removed from a melt may be silicon, sulfur, manganese, phosphorus, or carbon. These elements are not removed by direct chemical reaction but by indirect reaction. For a basic refining process, limestone is added as a flux, and iron ore or mill scale as an oxidizing agent. The reactions may be shown as follows (Clapp and Clark, 1944):

$$CaCO_3 \longrightarrow CaO + CO_2$$

$$CO_2 + Fe \longrightarrow FeO + CO$$

$$Si + 2FeO \longrightarrow SiO_2 + 2Fe$$

$$C + FeO \longrightarrow CO + Fe$$

$$Fe_3C + FeO \longrightarrow CO + 4Fe$$

$$3SiO_2 + 2FeO \longrightarrow (FeO)_2 \cdot (SiO_2)_3 \text{ (Slag)}$$

$$Mn + FeO \longrightarrow MnO + Fe$$

$$MnO + SiO_2 \longrightarrow MnO \cdot SiO_2 \text{ (Slag)}$$

$$2Fe_3P + 8FeO \longrightarrow (FeO) \cdot P_2O_5 + 11Fe$$

Sulfur is partially removed in the following manner, $CaO + FeS \rightarrow CaS + FeO$. The resulting CaS is taken up by the slag.

For an acid refining process the sequence of reactions can be shown in a similar manner as follows (Clapp and Clark, 1944):

$$2Fe + O_2 \longrightarrow 2FeO$$

$$3Fe + 2O_2 \longrightarrow Fe_3O_4$$

$$Si + 2Fe_3O_4 \longrightarrow SiO_2 + 6FeO$$

$$Si + 2FeO \longrightarrow SiO_2 + 2Fe$$

$$Mn + Fe_3O_4 \longrightarrow MnO + 3FeO$$

$$Mn + FeO \longrightarrow MnO + Fe$$

$$4C + Fe_3O_4 \longrightarrow 4CO + 3Fe$$

$$C + FeO \longrightarrow CO + Fe$$

The metallic oxides and silicon then form slags according to the equations:

$$FeO + SiO_2 \longrightarrow FeO \cdot SiO_2$$

$$2FeO + 3SiO_2 \longrightarrow (FeO)_2 \cdot (SiO_2)_3$$

$$MnO + SiO_2 \longrightarrow MnO \cdot SiO_2$$

$$2MnO + 3SiO_2 \longrightarrow (MnO)_2 \cdot (SiO_2)_3$$

Steel-refining processes are usually accomplished in the open hearth furnace, the electric furnace, or the Bessemer converter.

Open-hearth furnaces have an approximate range of 40 to 550 tons' capacity per heat with most falling in the 100- to 200-ton range. Because of the large capacities of these furnaces, they lend themselves to large-volume steel production.

The three types of electric furnaces used are the direct-arc, the indirect-arc, and the induction. Electric furnaces are most often used where only small quantities of pig iron are readily available and where remelting of steel scrap, or small heats of special alloys are required. Sometimes these furnaces are used with open-hearth furnaces. In such cases, the steel is first processed in an open-hearth furnace and is then further refined or alloyed in an electric furnace.

Still in limited use today is the Bessemer converter. It consists of a pear-shaped vessel or converter, mounted on trunnions and easily tilted for charging and pouring. Oxidation of manganese, silicon, and carbon is accomplished by blowing air through the molten metal. Converters have been largely replaced owing to the increased production rates achieved by the open-hearth and electric furnaces.

In 1960 over 4 million tons of steel (2.7 percent of the total production) was produced by a recently developed process called the oxygen process. This is similar to the Bessemer process in that an oxidizing gas, oxygen instead of air in this case, is blown through the molten metal. This oxygen-blowing process can be used as a rapid source of heat control to increase the temperature of the furnace bath or may be used to refine the metal by oxidizing the undesirable elements in the bath. The principal advantage of this process is that it shortens the refining time and thus reduces production costs.

In the oxygen process, pure oxygen is immediately available to promote oxidation of the impurities in the bath. If oxygen is used to reduce the carbon content, then carbon monoxide and iron oxide are formed, some oxygen remaining in the bath. Figure 168 shows this relationship for various bath carbon percentages. In the oxygen process, the oxygen also reacts at a slower rate with other elements such as silicon, manganese, and chromium to reduce the content of these elements in the molten bath.

Steel-making capacity in the United States by type of furnace is depicted in Table 64. In 1960 over 85 percent of the steel-making operating capacity was represented by 906 open-hearth furnaces, 10 percent, by 301 electric furnaces, and 5 percent, by 31 Bessemer converters and 12 oxygen process furnaces. Total operating capacity was 148,571,000 tons.

Table 64. NUMBER AND CAPACITIES OF STEEL FURNACES OPERATED IN UNITED STATES, 1960 (Steel Facts, American Iron and Steel Institutes, New York, New York)

Furnace type	Number	Capacity, tons
Open hearth	906	126,621,630
Electric	301	14,395,940
Bessemer	31	3,396,000
Oxygen process	12	4,157,400

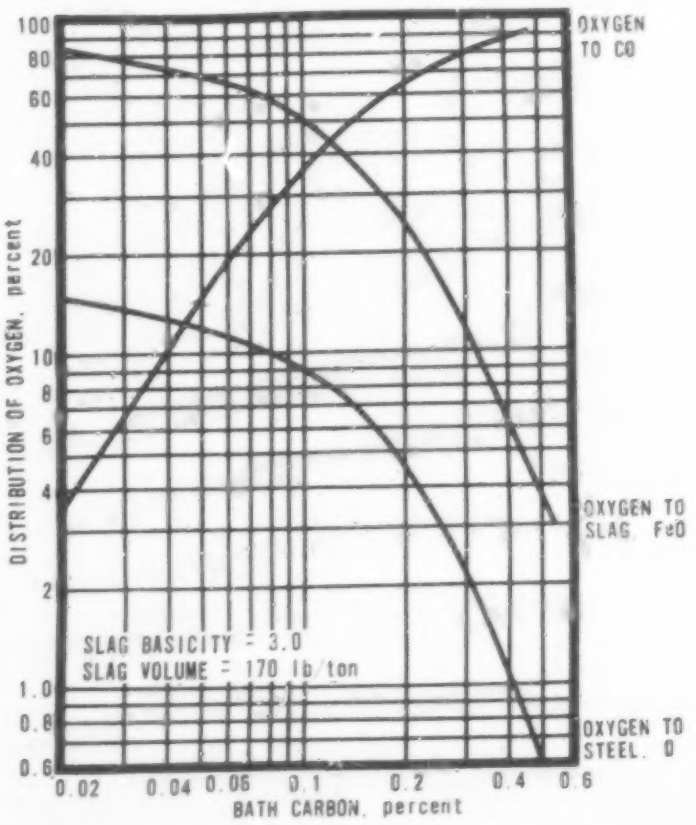


Figure 168. The oxygen reaction in molten steel (Obrzut, 1958).

The air contaminants vented from steel-melting furnaces include gases, smoke, fumes, and dusts. The quantities of these contaminants in the effluent gas stream depend upon the types of material charged to the furnace. The gaseous emissions result from the combustion of fuels and other combustible contaminants in the furnace charge and from the refining process. Smoke emissions result from incomplete combustion of the combustibles in the furnace charge or of furnace fuels. Particulate emissions originate partially from dirt and impurities in the charge, but the major quantity results from the refining process.

A study of the chemical reactions of the refining processes reveals that a large portion of the particulate matter is emitted from steel furnaces in the form of metallic oxides. These characteristics are illustrated in Table 65, where the results of a spectrographic analysis of the particulate discharge from an open-hearth furnace are given, and in Table 66, which gives a typical analysis of the particulate discharge from an electric-arc furnace. These fume emissions or metallic oxides are very small, 65 to 70 percent falling into the 0- to 5-micron range. Table 67 shows a size analysis of the particulate emissions from an open-hearth furnace and two electric-arc furnaces along with other data. For a visual concept of particle size and shapes, electron photomicrographs of fumes from an electric-arc furnace and an open-hearth furnace are shown in Figures 169 and 170.

OPEN-HEARTH FURNACES

The open-hearth furnace, which features the regenerative principle, was invented by William Siemers in 1858. Although many improvements

Table 65. SPECTROGRAPHIC ANALYSIS OF PARTICULATE DISCHARGE FROM AN OPEN HEARTH FURNACE[a]

Element	Approximate amount, %
Fe	Remaining amount
Zn	10 to 15
Na	1 to 2
K	1 to 2
Al	5
Ca	5
Cr	2
Ni	2
Pb	5
Si	5
Sn	1
Cu	0.5
Mn	0.5
Mg	0.1
Li	Trace
Ba	Trace
Sr	Trace
Ag	0.05
Mo	Trace
Ti	Trace
V	0.05

[a] These data are qualitative only and require supplementary quantitative analysis for actual amounts.

Table 66. TYPICAL EMISSIONS FROM AN ELECTRIC-ARC FURNACE (Coulter, 1954)

Component	Weight %
Zinc oxide (ZnO)	37
Iron oxides	25
Lime (CaO)	6
Manganese oxide (MnO)	4
Alumina (Al_2O_3)	3
Sulfur trioxide (SO_3)	3
Silica (SiO_2)	2
Magnesium oxide (MgO)	2
Copper oxide (CuO)	0.2
Phosphorus pentoxide (P_2O_5)	0.2

and refinements have been made since then, the process remains essentially the same. There are roughly four methods of making basic open-hearth steel in the United States. These are classed according to the iron-bearing materials in the charge as follows (Kirk and Othmer, 1947):

1. Hot metal (pig iron) and molten steel. By this method, iron from the blast furnace, and steel from the Bessemer converter are refined in the open-hearth furnace.

2. Cold steel scrap and cold pig iron. This combination is used by plants that have access to supplies of inexpensive scrap and do not have a blast furnace.

3. All steel scrap. This process is uncommon in the American steel industry.

4. Steel scrap and molten pig iron. Most of the integrated steel plants use this method, which is the predominant process in the United States and Canada.

In the last method, a typical initial charge consists of 55 percent cold pig iron and 45 percent steel scrap. Limestone and iron ore, equal in quantity to approximately 7 and 4 percent, respectively, of the total weight of the cold metal charged, are also added. If molten pig iron cannot be obtained in sufficient quantity to complete the initial charge, more cold pig is charged with the scrap, and the entire mass is heated in the furnace. The process continues for approximately 2 hours until the scrap has reached a temperature of about 2,500°F and has slightly fused. Molten pig is then added and a lively action occurs in which almost all the silicon, manganese, and phosphorus, and part of the carbon are oxidized. The first three elements form compounds that slag with iron oxide and join the iron and lime silicates that are already melted. The ore acts on the carbon for 3 or 4 hours longer while the limestone forms carbon dioxide and completes the purification. The lime boil lasts for another 2 or 3 hours and the heat is then ready to be adjusted for final carbon content by adding pig iron, ore, or oxygen gas. The described operation is commonly divided into three phases consisting of the ore boil, the lime boil, and the working period.

The heat for the process is provided by passing a luminous flame with excess air over the charged materials. The combustion air is alternately preheated by two regenerating units, which, in turn, are heated by the products of combustion discharging from the furnace.

The Air Pollution Problem

Air contaminants are emitted from an open-hearth furnace throughout the process, or heat, which lasts from 8 to 10 hours. These contaminants can be categorized as combustion contaminants and refining contaminants. Combustion contaminants result from steel scrap, which contains grease, oil, or other combustible material, and from the furnace fuel.

The particulate emissions that occur in greatest quantities are the fumes, or oxides, of the various metal constituents in the steel alloy being made. These fumes are formed in accordance with the

Table 67. DUST AND FUME DISCHARGE FROM STEEL FURNACES

Test number	1	2	3
Furnace data			
Type of furnace	Electric arc	Electric arc	Open hearth
Size of furnace	2 ton and 5 ton[a]	50 ton	50 ton
Process wt, lb/hr	3,755	28,823	13,300
Stack gas data			
Volume, scfm	7,541	23,920	14,150
Temperature, °F	125	209	1,270
Dust and fume data			
Type of control equipment	None	None	None
Concentration, gr/scf	0.1245	0.5373	1.13
Dust emissions, lb/hr	8.05	110.16	137
Particle size, wt %			
0 to 5 μ	67.9	71.9	64.7
5 to 10 μ	6.8	8.3	6.79
10 to 20 μ	9.8	6.0	11.9
20 to 44 μ	9.0	7.5	8.96
> 44 μ	6.5	6.3	7.65
Specific gravity	--	3.93	5

[a]Both furnaces are vented by a common exhaust system and were tested simultaneously.

refining chemistry previously discussed. The concentration of the particulates in the gas stream varies over a wide range during the heat, from 0.10 to a maximum of 2.0 grains per cubic foot (Allen et al., 1952). An average is 0.7 grain per cubic foot, or 16 pounds per ton of material charged. The test results in Table 67 for the open-hearth furnace show that 64.7 percent of the emissions are below 5 microns in size. The control device selected must, therefore, be capable of high collection efficiencies on small particles.

Another serious air pollution problem occurring with open-hearth furnace operation is that of fluoride emissions. These emissions have affected plants, which in turn, have caused chronic poisoning of animals. Surveys have shown that fluorides are contained in some iron ores such as those mined in southern Utah. Control of fluoride emissions presents a problem because these emissions are in both the gaseous and particulate state.

Hooding and Ventilation Requirements

The design parameters for an open-hearth furnace control system for duct sizes, gas velocities, and so forth are the same as those to be outlined for the electric-arc furnace. In order to establish the volume of gases to be vented from the furnace, the maximum fuel input must be known:

Example 25

Given:

60-ton open-hearth furnace. Fuel input = 35 lb of U.S. Grade No. 6 fuel oil per min.

Problem:

Determine the volume of gases to be vented from the furnace stack to the air pollution control system.

Solution:

1. Volume of products of combustion from oil burners:

   One pound of U.S. Grade No. 6 fuel oil with theoretical air produces 186.1 scf gas (see Table D6 in Appendix D).

   $$V_{PC} = 35 \times 186.1 = 6,510 \text{ scfm}$$

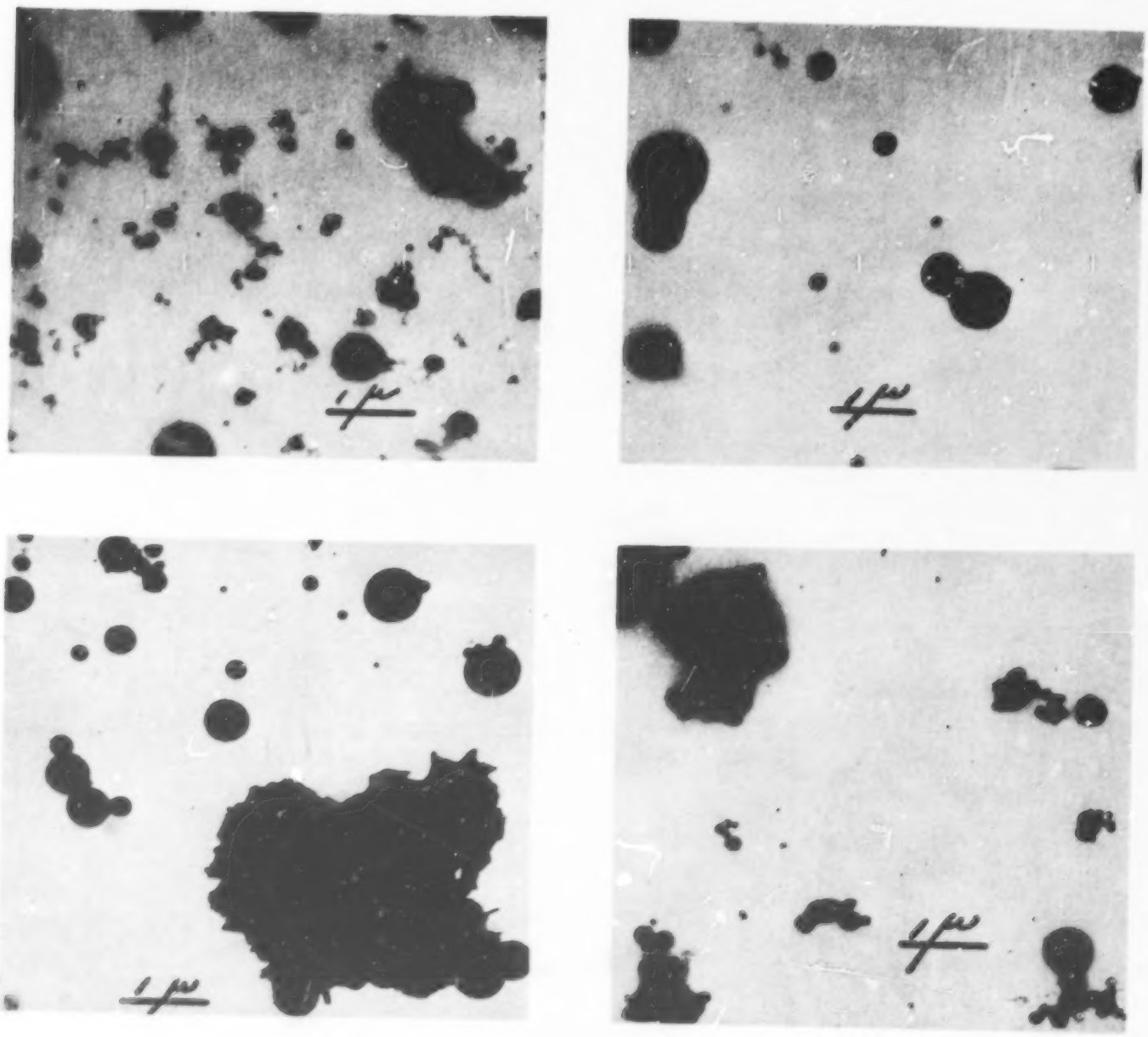


Figure 169. Electron photomicrographs of fumes from an electric furnace producing steel for castings (Allen et al., 1952).

2. Volume of air infiltrated through leaks owing to reversing valves, stack dampers, cracks in bricks, and so forth:

Assume the average 150 percent excess air (combustion and infiltration) usually found in the stacks of regenerative furnaces. Theoretical air for 1 pound of U.S. Grade No. 6 fuel oil is 177.2 scf (see Table D6 in Appendix D).

$$V_{EA} = 35 \times 177.2 \times 1.5 = 9,320 \text{ scfm}$$

3. Total volume at 60°F to air pollution control equipment:

$$V_{T60} = V_{PC} + V_{EA}$$
$$= 6,510 + 9,320 = 15,830 \text{ scfm}$$

The temperature of the furnace gases leaving the regenerator will be approximately 1,300°F. In some installations, this heat source is used to generate steam by delivering the gases to a waste heat boiler in which the temperature would be reduced to about 500°F.

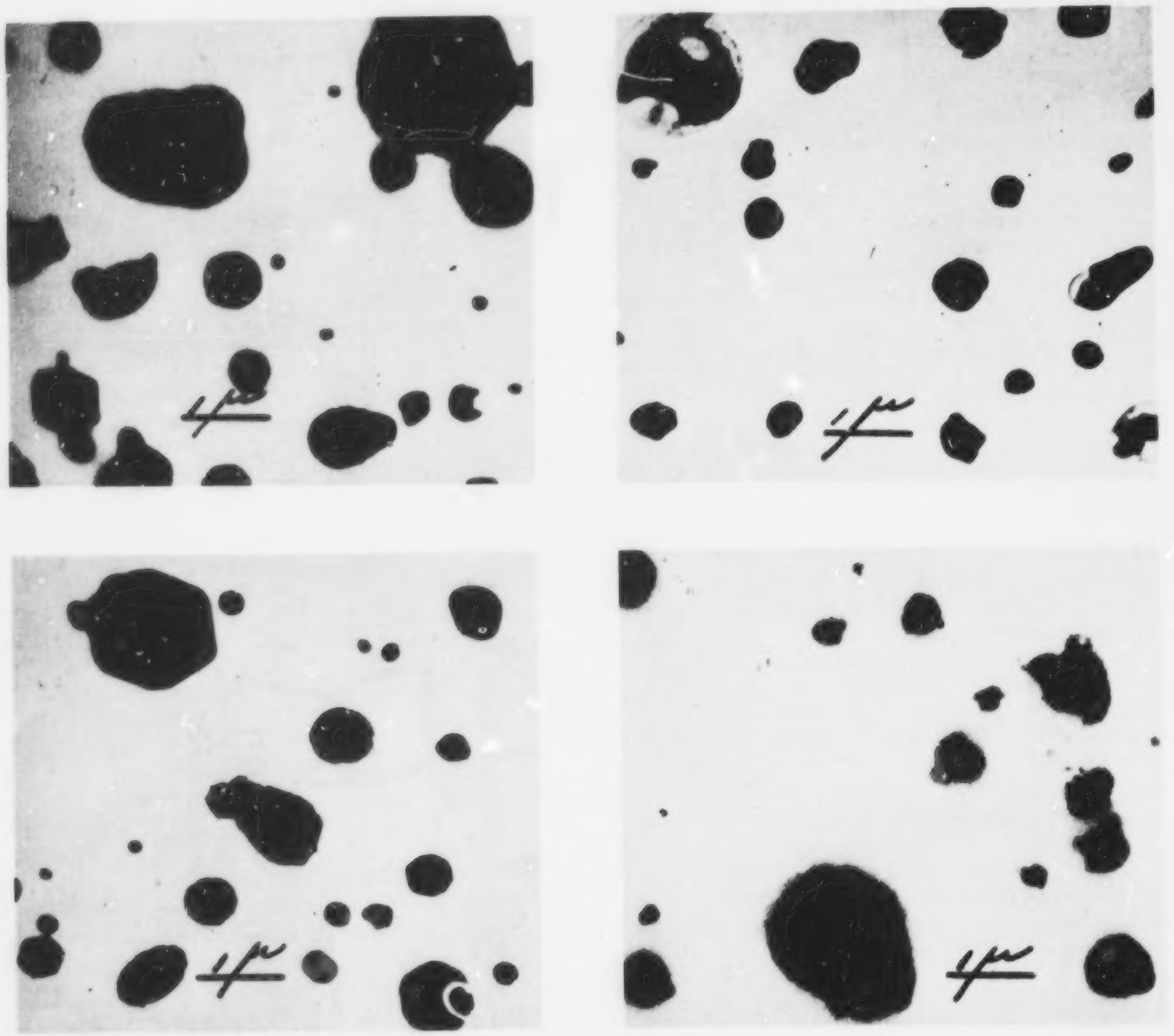


Figure 170. Electron photomicrographs of fumes from a cold-metal open-hearth steel furnace (Allen et al., 1952).

4. Total volume of the air pollution control equipment at 500°F operating temperature:

$$V_{T500} = 15,830 \times \frac{460 + 500}{460 + 60} = 29,200 \text{ cfm}$$

Since the efficient operation of the open-hearth furnace requires that all the products of combustion, along with the air contaminants created in the furnace, are to be conducted through the regenerator and then to a stack, it is necessary only to direct the flow from the stack through suitable ductwork to the control system. The size of the blower must, of course, be increased to overcome the additional resistance introduced by the control system.

Air Pollution Control Equipment

Open-hearth furnaces have been successfully controlled by electrical precipitators. On some installations, the control system has been refined by installing a waste heat boiler between furnace and control device. In this manner, heat is reclaimed from the furnace exhaust gases, and at the same time, the gases are reduced in temperature to within the design limits of the control device. In Table 68 are shown test results of a control system wherein the waste heat boiler and electrical precipitator vent an open-hearth furnace. This test was made on one of four control systems installed to serve open-hearth furnaces. These control systems are shown in Figure 171.

Table 68. DUST AND FUME EMISSIONS FROM AN OPEN-HEARTH FURNACE SERVED BY AN ELECTRICAL PRECIPITATOR

Furnace data:	
Type of furnace (constructed 1916)	Open hearth
Size of furnace, tons	63
Test interval	1 hr during heat working period
Fuel input	Natural gas, 21,000 cfh
	Fuel oil, 1.4 gpm
Waste heat boiler data:	
Gas volume, inlet, scfm	14,900
Gas temperature, inlet, °F	1,330
Gas temperature, outlet, °F	460
Water in waste gas, %	12.4
Steam production (average), lb/hr	8,400
Precipitation data:	
Gas volume, scfm	14,900
Dust and fume concentration (dry volume)	
Inlet, gr/scf	0.355
Outlet, gr/scf	0.004
Inlet, lb/hr	39.6
Outlet, lb/hr	0.406
Collection efficiency, %	98.98

The factors to be considered in designing an electrical precipitator to control the emissions from an open-hearth furnace are the same as those that will be described next.

Electric-Arc Furnaces

The electric-arc furnace lends itself to accurate control of temperature and time of reaction for alloy composition. These advantages are achieved because no harmful gases are emitted from an electric arc that would otherwise produce an adverse effect upon the metal being refined. Steel may be produced in an arc furnace by either the basic or the acid process. The furnace may be charged with molten metal from an open-hearth furnace (an operation known as duplexing), or it may be charged with cold steel scrap. Owing to the close control that can be achieved, low-grade scrap can be refined to meet close specifications of the various steel alloys.

After the furnace has been charged with metal, fluxes and other additions required to accomplish the refining chemistry are charged according to schedule. The additions vary depending upon the steel being produced and the metal charged. Lime is usually a basic addition along with others, such as sand, fluorspar, iron ore, carbon, pig iron, and other alloying elements. The operation then continues in three phases: (1) The oxidizing period, in which the undesirable elements are oxidized from the metal and removed as slag, (2) the reducing period, in which oxygen is removed from the metal mostly through the reaction with carbon, and (3) the finishing period, in which additions are made to bring the alloy within the desired specifications. The make-up of a typical charge to an electric-arc furnace is shown in Table 69.

Table 69. TYPICAL CHARGE FOR AN ELECTRIC-ARC FURNACE (Coulter, 1954)

Material	Weight %
Fluxes, carbon, and ore	5
Turnings and borings	7
Home scrap	20
No. 2 baled scrap	25
Miscellaneous scrap (auto, etc)	43

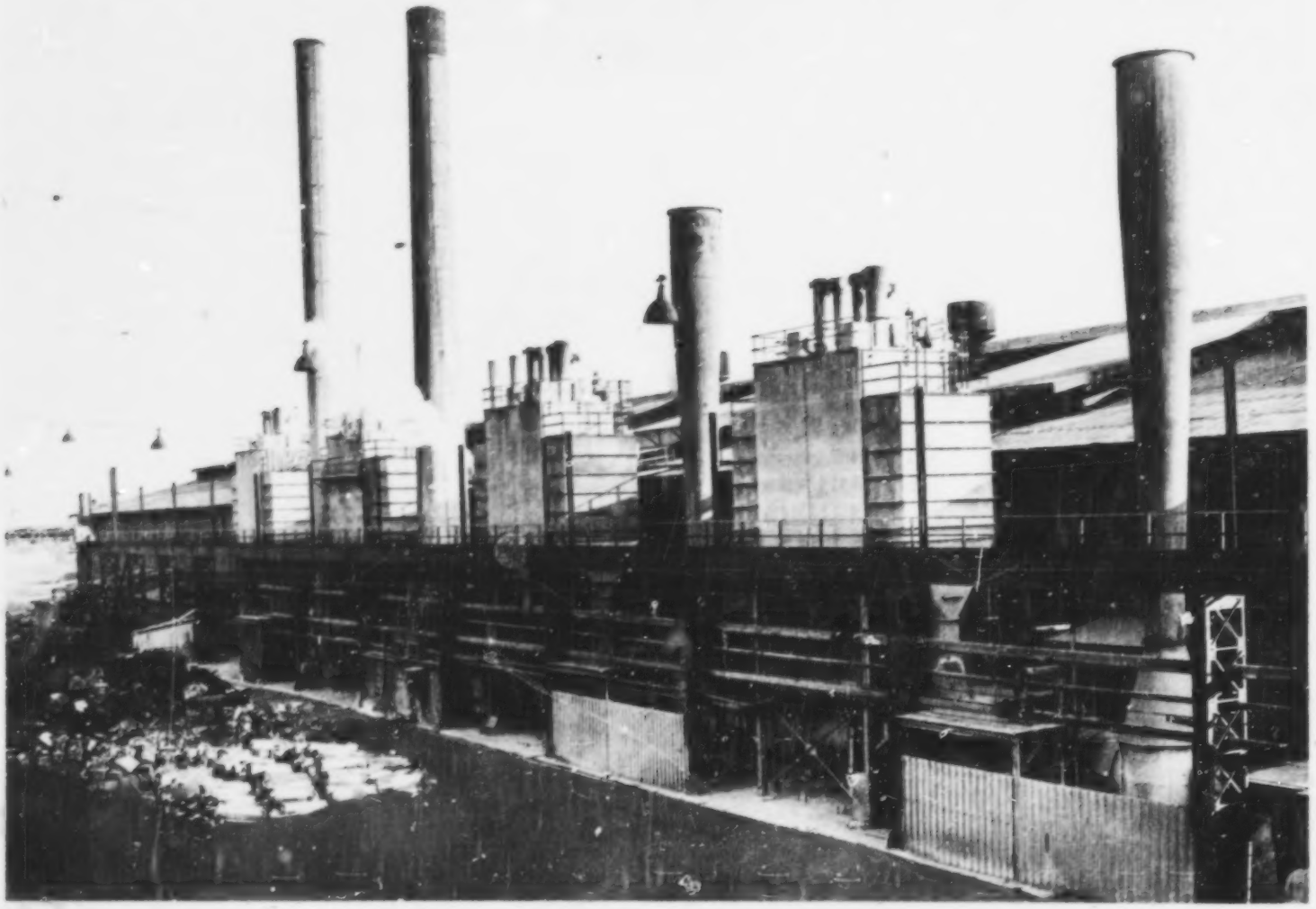


Figure 171. Electrical precipitators serving open-hearth furnaces.

The Air Pollution Problem

The quantity and type of fumes emitted from an electric-arc furnace depend upon several factors: Furnace size, type of scrap, composition of scrap, cleanliness of scrap, type of furnace process, order of charging materials, melting rate, refining procedure, and tapping temperature. A large portion of the fumes generated in a furnace is retained in the slag; however, sizable quantities of fumes escape and are discharged from the furnace vent. Table 70 shows emission data for several arc furnaces, which vary from 4.5 to 29.4 pounds per ton of metal melted. Most of the emissions originate during the first half of the heat. Figure 172 shows a curve of emission rates during the single heat.

Hooding and Ventilation Requirements

Before the emissions can be collected they must first be captured through some suitable hooding arrangement at the furnace and must then be conveyed to a collection device that has a high collection efficiency on small particles.

Three types of hooding arrangements can be installed. The first is a canopy-type hood, which is suspended directly over the furnace (Figure 173). A hood such as this has serious deficiencies in that it must be mounted high enough above the furnace to clear the electrodes and not interfere with the crane when overhead charging is employed. As the distance between the furnace and hood is increased, the volume of air to be inspirated into

Table 70. ELECTRIC-ARC STEEL FURNACE EMISSION DATA (Brief et al., 1956)

Case	Rated furnace size, tons	Average melting rate, tons/hr	Cycle time, hr	Fume emission/ton melted, lb/ton	Furnace process
A	50	18.3	4	9.3[c]	
	75	23.5	4	18.6[d]	Basic, single slag
	75	23.5	4	--	
B	50[a]	14.4	4	7.6	
	50[a]	13.6	4	6.9	Basic, single slag
	75[a]	21.9	4	12.3	
	3	1.5	2	12.6	Acid, oxygen blow
	3	1.1	2	7.6	Acid, oxygen blow
	6	3.1		10.4	
	10	6.6	2	5.5	Basic, oxygen blow
	10	5.4	2	5.2	Basic, oxygen blow
	2[b]	1.5[b]		13.4	
C	3	1.9	2	4.5	Acid
	3	1.6	2	5.8	Acid
	3	1.9	2	5.7	Acid
	6	2.6	2.33	15.3	
	6	3.0	2	12.8	
D	18	5.4	3	6.1	
E	6	4.1	1.2	29.4	Acid, single slag
F	3	1.8	1.75	12.7	Acid, single slag

[a]Refer to same furnace as case A.
[b]Two 2-ton furnaces operating in parallel.
[c]Average for one 50-ton and two 75-ton furnaces processing normal scrap.
[d]Average for one 50-ton and two 75-ton furnaces processing dirty, sub-quality scrap.

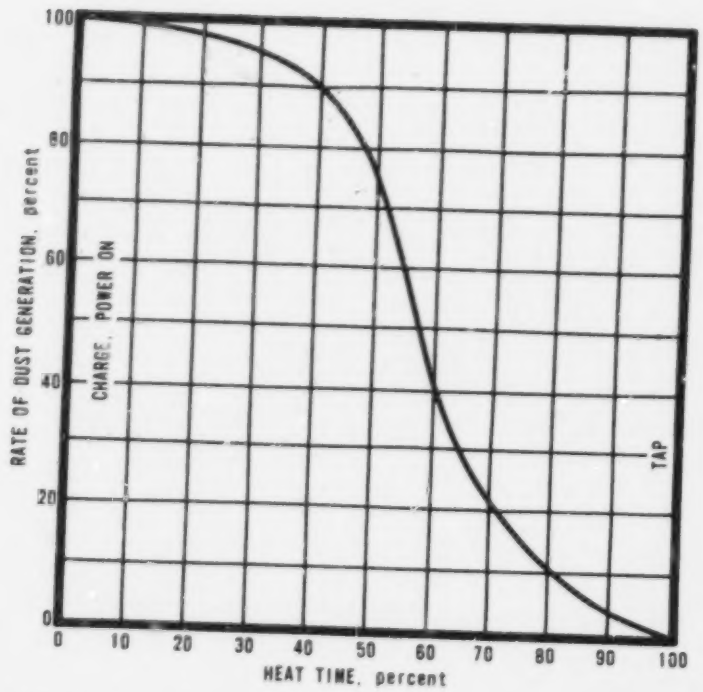


Figure 172. Curve showing rate of fume emission during a heat of an electric-arc furnace (Coulter, 1954).

the hood must also be increased to achieve satisfactory capture of the furnace emissions. For this reason the canopy hood has not proved practical on large furnace installations since tremendous volumes of air must be handled.

The second hood type (Figure 174) is called a plenum roof. Here a flat hood is attached to the furnace roof ring and has pickup openings over the charging door, the pouring spout, and the electrode openings. Holes in the top of the hood admit the electrodes. This type of hood must have a telescoping or swivel connection, or both, to the exhaust system to permit tilting and pouring operations of the furnace. For top-charge furnaces, the hood must be sectioned and installed with an exhaust system disconnect joint to permit roof removal. Because of this feature, these furnaces are necessarily uncontrolled during the charging operation. This type of hood is shown in Figure 175. The 25-ton furnace with plenum hood is one of three furnaces venting to the baghouse.

In the third type of hood, the furnace roof is tapped and connected directly to the exhaust system, which permits the furnace to serve as its own hood. With

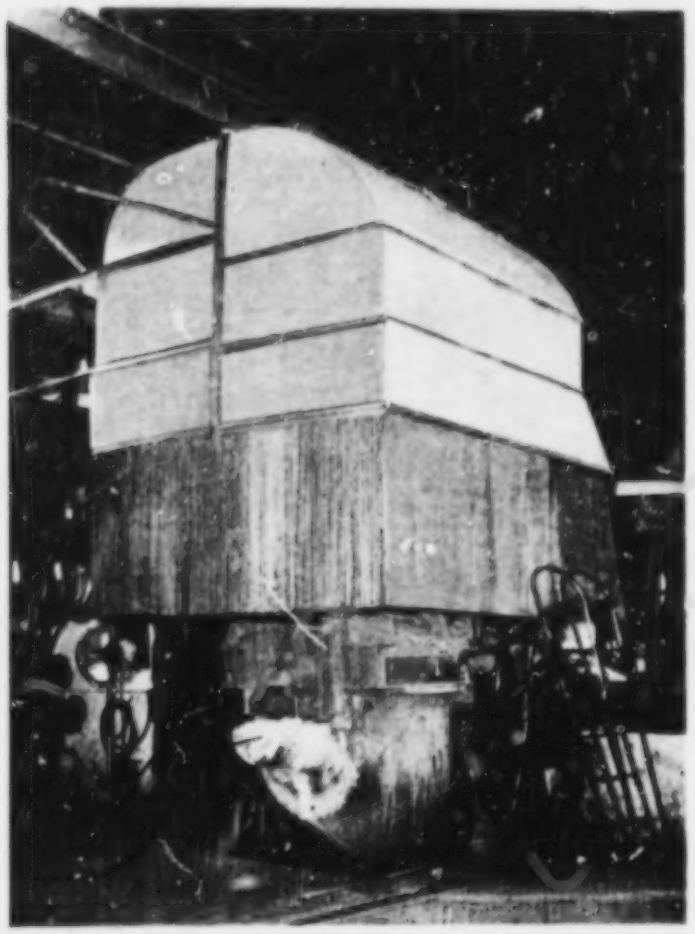


Figure 173. Electric-arc furnace venting to a canopy-type hood.

this arrangement, air is inspirated through all furnace openings and vented directly to the exhaust system. Here again, the furnace becomes uncontrolled when the roof is removed for charging. It is also uncontrolled when tilted during the pouring operation unless a telescoping and swivel duct connection is installed. Since this type of hooding results in high effluent gas temperatures from the furnace, flame and cinder traps should be installed on the larger furnaces, and some provision for cooling the gas stream may have to be made. This is particularly true if the charged scrap contains combustible contaminants. Depending upon the materials and type of construction, the duct connections to the furnace may have to be water jacketed for cooling. Figure 176 illustrates a roof tap with a stainless steel duct connection.

A hood should be designed so that a positive indraft of air through all hood openings will prevent escape of fumes. The design air volume to ventilate an electric-arc furnace with an integral hood is approximately 2,500 cfm per ton of charge. If a canopy-type hood is used, a velocity of 200 fpm should be maintained between the furnace and the hood (Committee on Industrial Ventilation, 1960). Design figures such as these must, however, be used with discretion, depending upon the individual furnace to be controlled. Table 71 contains design data for several actual installations.

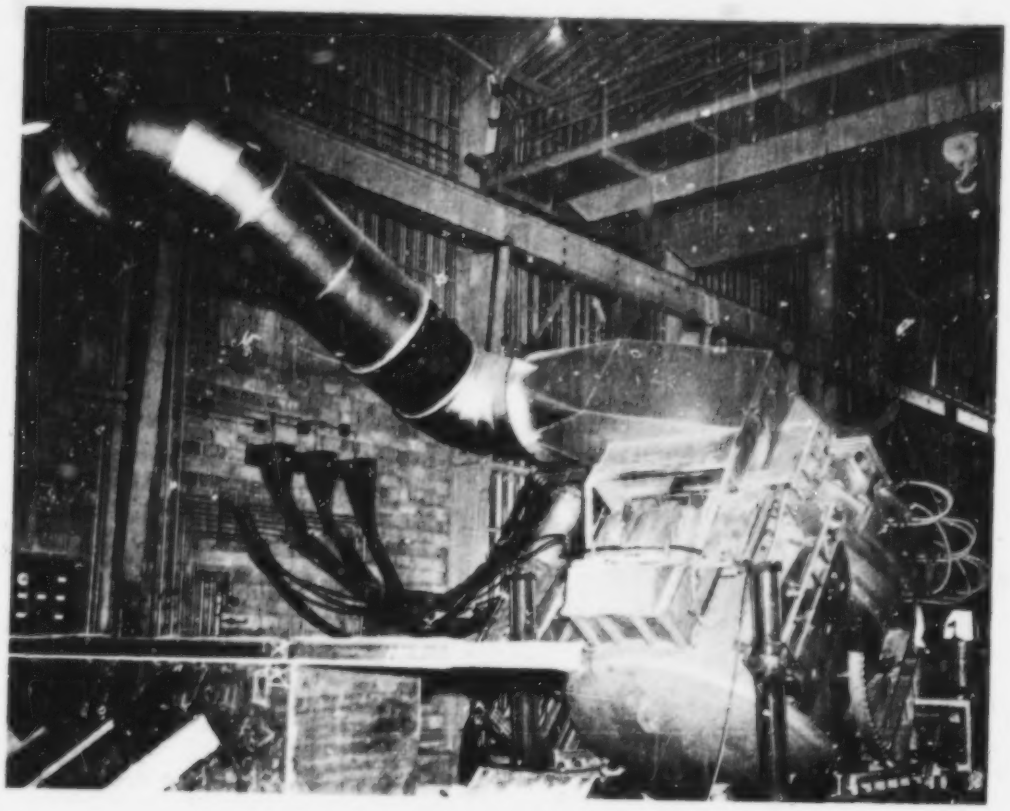
The duct system must be designed to maintain a satisfactory conveying velocity for the furnace emissions. These fine metallic fumes can be satisfactorily conveyed at a velocity of 3,500 fpm. Another design feature that must be considered is that of cooling the effluent gas stream to within operating temperature limits for cloth filters. With a canopy-type hood, large quantities of dilution air are taken in through the hood, which effectively reduce the effluent gas temperature. With the plenum roof and direct furnace tap, however, there are intervals when the effluent gas stream temperatures are excessive, and some type of cooling is required.

Cooling may be accomplished by radiation convection cooling columns, by water-spray nozzles, or by dilution air. In installations where cooling is required only during a short portion of the operating cycle, a dilution air damper can be installed in the exhaust system that automatically opens to prevent the gas stream's temperature from exceeding the limits of the filter cloth. The effects of these cooling methods upon duct, fan, and motor selection must be considered in designing the exhaust system. The introduction of water into an exhaust system invites accelerated corrosion.

Air Pollution Control Equipment

Baghouse dust collectors

The bagnouse control device must be designed with features that make its operation compatible with the operation of the furnace and exhaust system. The baghouse must have a filter area that efficiently removes the particulate matter from the gas stream. The filtering velocity should not exceed 2.5 fpm. Since high temperatures are reached periodically, Dacron or glass fiber are used for this service. Dacron can withstand temperatures up to 275°F, and glass fiber can withstand temperatures up to 500°F. Electric furnace fumes tend to agglomerate, and the bags must be shaken sufficiently to remove the collected fumes from the cloth surface. The temperature of the effluent gas stream must not be allowed to fall below the dewpoint in the baghouse, or blinding of the bags results. This, in turn, reduces the exhaust air volume, causing poor pickup of fumes at the source. Blinding of the bags also makes bag cleaning more difficult. The baghouse should be compartmented so that one section at a time can be isolated and bags shaken to allow continuous system operation. It should be equipped with hoppers that facilitate the removal of the collected ma-



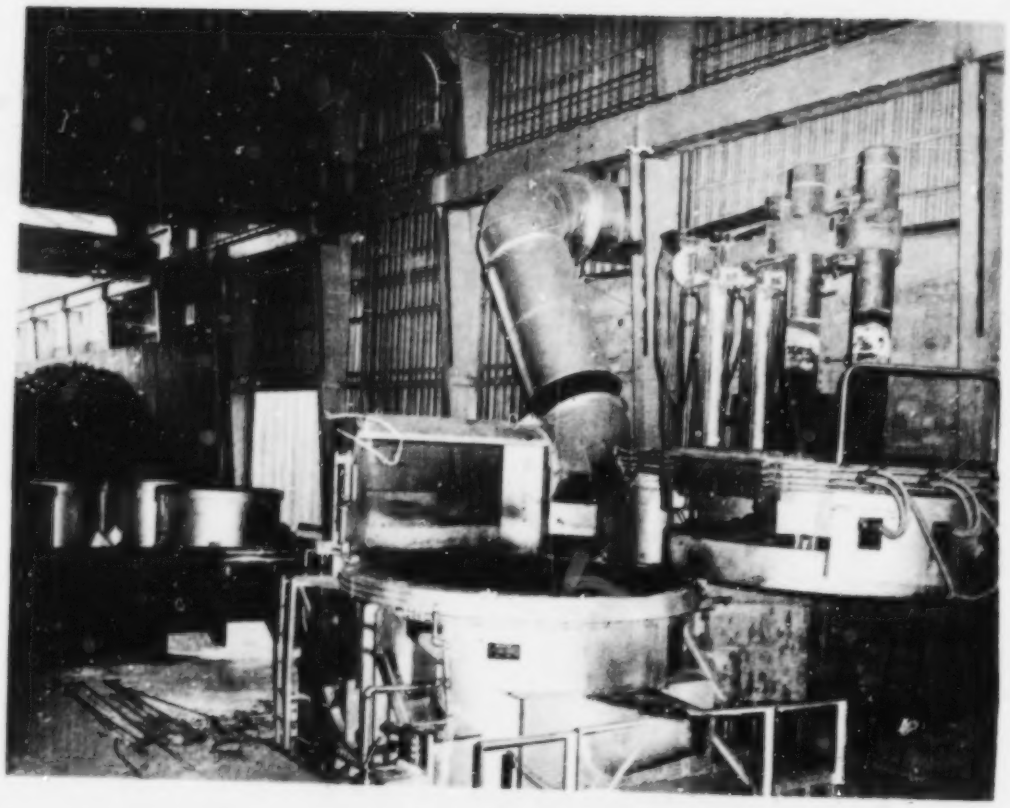


Figure 174. Close-fitting plenum-type hood serving an electric-arc furnace: (left) furnace filled with hood in place. (right) furnace with hood removed (Soule Steel Company, Los Angeles, Calif.).

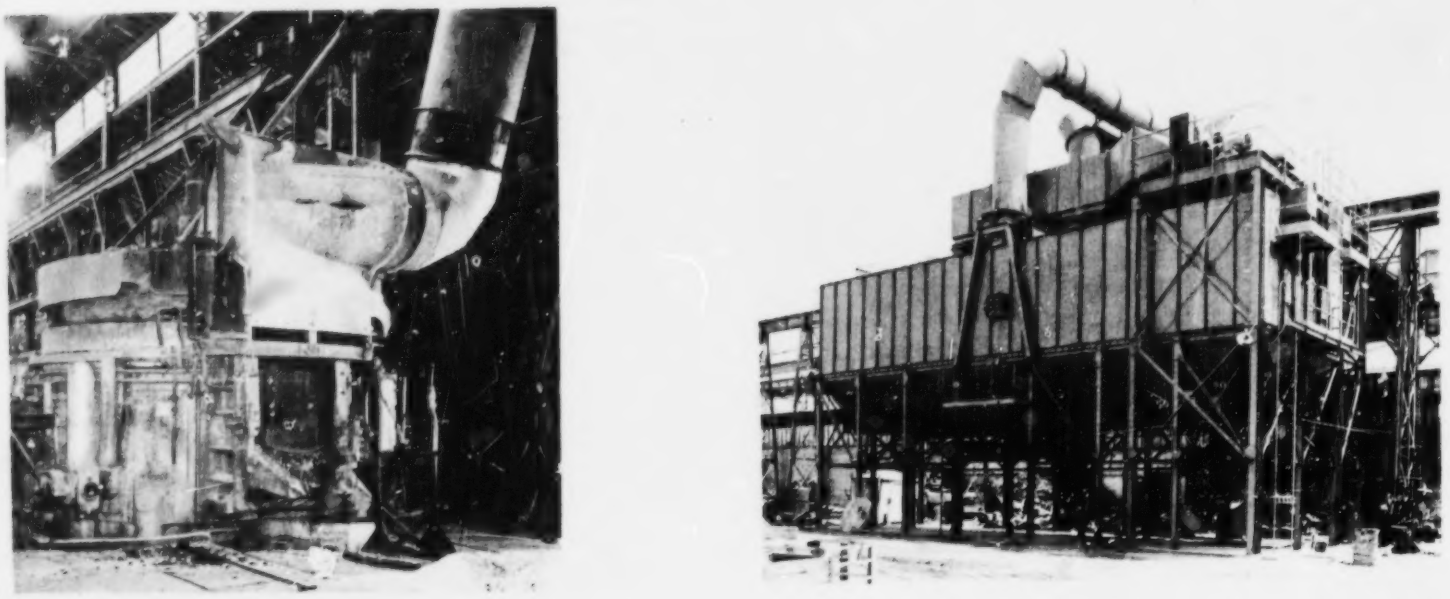


Figure 175. (Left) electric-arc furnace with plenum hood, (right) venting to a baghouse (National Supply, Torrance, Calif.).

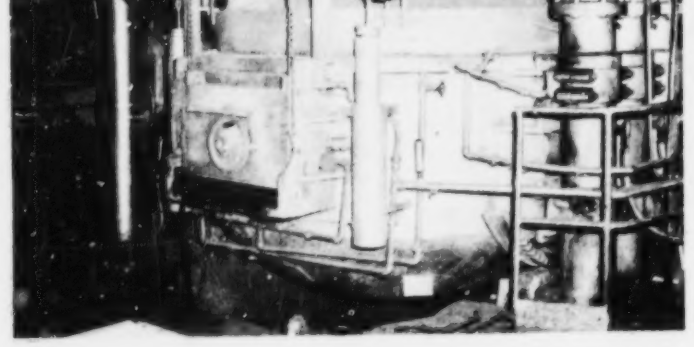


Figure 176. Direct roof tap on an electric-arc furnace (Alloy Steel and Metals Company, Los Angeles, Calif.).

terial. Screw conveyors are frequently installed on the hoppers as an aid for removing the material collected.

Control unit assembly must be constructed of materials that can withstand the temperatures of the furnace and the effluent gas stream. Provision should also be made to prevent sparks and burning material from entering the collector.

An outline of some of the design features of baghouses that serve electric steel-melting furnaces is included in Table 71. Only one of these installations was equipped for reverse air cleaning. This particular baghouse has been replaced with a conventional shake cleaning unit because of the high maintenance costs associated with the reverse air cleaning mechanism and because of the excessive bag wear.

In Table 72 are shown test results of air pollution control systems with baghouses serving electric-arc steel-melting furnaces. The collection efficiencies of the baghouses in tests 1, 2, and 3 are within the range of expected efficiencies for installations of this type. In tests 4 and 5 the collection efficiencies are subnormal, indicating malfunction of the systems. This was evident at the time of the tests from the visible discharge of dust and fumes from the baghouse outlets. An investigation disclosed that those two baghouses had many defective bags. The results are, however, reported to emphasize the necessity of checking the veracity of tests such as these.

Electrical precipitators

An electrical precipitator may be used to control the emissions from an electric-arc furnace. The fundamental design considerations for hooding, air volume cooling, duct sizing, and fan selection are the same as those outlined for baghouse control. The one major difference pertains to the conditioning of the effluent gas stream. A baghouse system should be designed so that the gas temperature remains below the maximum operating temperature of the cloth bags and above the dewpoint. For an electrical precipitator, control must be much more accurate. The apparent resistivity

Table 71. ELECTRIC STEEL FURNACE AND BAGHOUSE COLLECTOR DATA

	A	B	C	D	E	F	G	H
Total number of furnaces	3	1	1	1	4	3	2	2
Furnace nominal size, tons	25, 6, 2	15	12	16	3/4, 3, 3, 3	2, 2, 1/2	3 2	3 3
Furnace actual charge, tons	25, 8, 2	17	14	19	3/4, 4-1/2, 4-1/2, 4-1/2	4, 4, 3/4	3-1/2, 2-1/2	3-1/3, 3-1/3
Furnace energy rating, kv-a	5,000, 5,000, 1,500	6,000	6,000	7,500	750, 1,400 1,800, 1,800	1,500, 1,500, 800	1,500, 1,000	1,750, 1,750
Average heat time, hr	6-1/2, 3-1/2, 3	2	2-1/2	2-1/2	2, 2, 2, 2	2, 2, 2	1-1/2, 2	2, 2
Oxygen blow	Yes	Yes	No	No	Yes	No	Yes	Yes
Design volume of blower, cfm	60,000	47,000	60,000	60,000	32,000	26,200	13,800	8,000
Gas volume/ton charged, cfm/ton	2,140[a]	2,610	4,280	3,160	2,370[b]	2,760	3,940[c]	1,200
Type of baghouse	Compartmented tubular	Sectioned tubular	Compartmented tubular	Sectioned tubular	Sectioned cloth screen	Compartmented tubular	Compartmented tubular	Reverse air jet
Filter material	Dacron	Orlon	Orlon	Orlon	Cotton	Orlon	Orlon	Orlon
Filter area, ft^2	30,720	20,800	25,760	26,304	11,220	11,760	5,540	884
Filtering velocity, fpm	1.96	2.26	2.33	2.28	2.85	2.23	2.5	9.06
Shaking cycle, min	60	120	60	150	60	60	60	Continuous
Precleaner	None	None	Cinder trap	Cinder trap	WD roto-clones	None	None	Rotoclone
Hood type	Roof enclosure	Roof enclosure	Roof enclosure	Roof enclosure	Canopy	Roof enclosure	Roof enclosure	Direct furnace tap
Hood duct connection	Telescoping-articulating	Telescoping-articulating	Telescoping-articulating	Telescoping-articulating	Permanent	Slip flange	Slip flange	Special slip flange[d]
Cooling method	15,000-cfm blower	Long duct	Long duct and cinder trap	Long duct and cinder trap	Water	Long duct	Long duct	Water

[a] With all blowers and furnaces in use.
[b] A 3/4-ton furnace not included--standby.
[c] Only one furnace operated at a time--2-1/2 ton standby.
[d] Provides continuous connection to duct during slag and tap.

Table 72. DUST AND FUME EMISSIONS FROM ELECTRIC-ARC STEEL FURNACES WITH BAGHOUSE CONTROLS

Test number	1	2	3	4	5
Furnace data					
Type of furnace	3-electrode Direct arc	3-electrode Direct arc	Two, 3-electrode Direct arc	3-electrode Direct arc	3-electrode Direct arc
Size of furnace, tons	17	3-1/2	4/4	14	19
Process wt, lb/hr	13,700	4,250	3,380/5,131	17,650	22,300
Baghouse data					
Type of baghouse	Sectioned tubular	Compartmented tubular	Sectioned tubular	Compartmented tubular	Sectioned tubular
Filter material	Orlon	Orlon	Orlon	Orlon	Orlon
Filter area, ft^2	20,800	5,540	11,760	25,760	26,304
Filtering velocity, fpm	1.95	1.78	1.20	1.23	1.75
Dust and fume data					
Gas flow rate, scfm					
Inlet	38,400	10,300	12,960	18,700	42,300
Outlet	40,600	9,900	14,110	31,700	46,100
Gas temperature, °F					
Inlet average	172	135	129	186	167
Outlet average	137	106	121	139	153
Concentration, gr/scf					
Inlet	0.507	0.346	0.398	0.370	0.462
Outlet	0.003	0.0067	0.0065	0.0158	0.047
Dust and fume emission, lb/hr					
Inlet	166.9	30.5	44.2	59.3	167.5
Outlet	1.04	0.57	0.79	4.3	18.5
Control efficiency, %	99.4	98.1	98.2	92.7[a]	88.9[a]
Particle size, wt %					
Inlet, 0 to 5 μ	72.0	57.2	63.3	59.0	43.3
5 to 10	10.5	37.8	17.7	33.1	17.7
10 to 20	2.7	3.4	8.0	4.9	6.4
20 to 40	4.7	1.6	8.1	3.0	14.60
> 40	10.1	0	2.9	0.0	18.0
Outlet	100% < 2 μ	100% < 1 μ	100% < 2 μ	72% < 5 μ	75% < 5 μ

[a]An investigation disclosed that poor efficiencies were due to defective bags in the baghouse.

of the material to be collected must first be determined. After this is known, the condition of the gas stream, and the temperature and humidity that will result in the most efficient collection can be determined. Efficient collection usually falls within a narrow temperature range, in which case the conditioning system must be designed to maintain the effluent gas stream within that range. Figure 177 shows the relationship between temperature, humidity, and collection efficiency for an electrical precipitator serving an electric-arc furnace in a specific installation. For this particular installation an acceptable efficiency was not realized until the gas temperature was maintained below 127°F and the humidity above 49 percent. Table 73 shows operating data for two installations of electrical precipitators serving electric-arc furnaces.

One general equation (Brief et al., 1956) for expressing precipitator efficiency is

$$E = 1 - K^{\frac{L}{V}} \qquad (100)$$

where

E = collection efficiency

K = precipitation constant (always less than unity and dependent upon the resistivity of the fume for a specific degree of gas conditioning)

L = electrode length, ft

V = volumetric flow rate, cfm.

This equation shows some of the factors that must be considered before the control system can be designed. Factors such as efficiency required, resistivity of fume, gas conditioning, geometry of precipitator, and others should all be discussed with a manufacturer of electrical precipitators before the design of the control system is formulated. General design information on electrical precipitators has been discussed in Chapter 4.

Water scrubbers

Water scrubbers have been used in many processes in which some contaminant must be removed from a gas stream. These same scrubbing methods have been used to control the emissions from electric-arc steel furnaces with varied results.

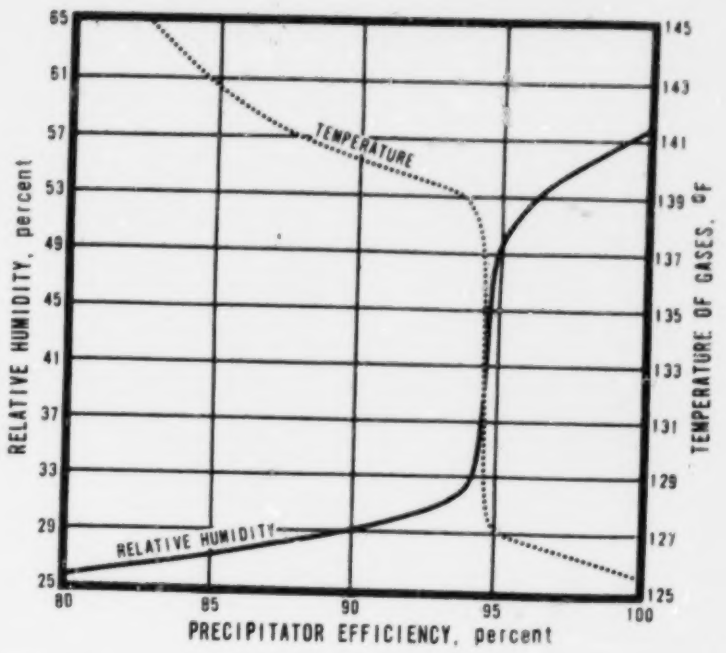


Figure 177. Curves showing effects of variation of the gas stream's temperature and humidity upon efficiency of a specific electrical-precipitator installation (Coulter, 1954).

Table 73. OPERATING DATA OF ELECTRICAL-PRECIPITATOR CONTROL SYSTEMS SERVING ELECTRIC-ARC FURNACES (Brief et al., 1956)

Case	A	B
Operational data		
Inlet gas volume, cfm	105,000	33,500
Inlet gas temperature, °F	127	80
Absolute humidity, lb/lb dry gas	0.045	Ambient
Inlet fume concentration, gr/ft^3	0.68[a] to 1.35[b]	0.115
Electrical-precipitator data		
Type	High-eff plate	Exp metal plate
Rectification	Mech, full wave	Mech, full wave
Size	30 ducts, 10 in. x 18 ft x 18 ft	19 ducts, 8-3/4 in. x 17 ft 6 in. x 18 ft
Gas velocity, fps	3.9	2.3
Gas retention time, sec	4.6	7.8
Electrode length	11,880	7,550
L/V ratio, $\frac{\text{electrode length}}{\text{volumetric rate}}$, sec/ft^2	6.8:1	13.6:1
Gas conditioner data		
Type	2-stage evaporative cooler	Radiation and tempering air cooler
Collection efficiency	97 + %	92%

[a]Average for one 50-ton and two 75-ton furnaces processing normal scrap.
[b]Average for one 50-ton and two 75-ton furnaces processing dirty, subquality scrap.

Table 74 shows the results of six tests on water scrubbers serving electric-arc steel-melting furnaces. Wet collectors collect only the larger particles and allow the submicron particles to pass through and be discharged to the atmosphere. These submicron particles cause the greatest diffusion of light and thus produce the greatest visual opacity. A venturi scrubber can be operated at greater efficiencies than those achieved by the scrubbers depicted in Table 74. A basic disadvantage of many scrubbers is that their efficiency of collection is proportional to their power input; thus, if a scrubber has the feature of high collection efficiency, the power input required to realize this high efficiency is also large. In any event, the decision to install a scrubber over some other type of control device depends principally upon the collection efficiency required and the comparative costs of installation and operation.

ELECTRIC-INDUCTION FURNACE

The electric-induction furnace uses the material to be heated as a secondary of a transformer. When a high-frequency current is applied to the furnace coils, an electromagnetic field is set up in the core or space occupied by the metal to be melted. This high-density electromagnetic field induces currents in the metal, causing it to heat and melt. These furnaces range in size from 30 pounds' to 8 tons' capacity. They are not well adapted to a refining process and, for the most part, are used for preparation of special alloys, or for certified true heats, or for investment castings.

The Air Pollution Problem

The fume emissions from an electric-induction furnace processing steel alloys have the same characteristics as those from electric-arc furnaces. Since a high degree of control is exercised in preparing alloys in this type of furnace, metals contaminated with combustible elements such as rubber, grease, and so forth are not charged to the furnace. This practice eliminates the need for control of combustible contaminants. The quantity of contaminants emitted from induction furnaces processing steel alloys varies. The factors affecting the fume generation include composition of alloy, method of making the alloy addition, temperature of the melt, and size of the furnace. When these factors are controlled, some steel alloys can be made without the need of air pollution control equipment.

Hooding and Ventilation Requirements

Since induction furnaces are relatively small, the canopy-type hood is readily adaptable to capturing the fumes. Recommended hood indraft velocities vary from 200 to 500 fpm, depending upon the hood, furnace geometry, cross-drafts, and temperatures involved. The following example problem shows a method of calculating ventilation requirements for a canopy-type hood serving an induction furnace:

Example 26

Given:

1,000-lb capacity electric-induction steel melting furnace

Pouring temperature = 3,000°F

Diameter of crucible = 2 ft

Surface area of molten metal = 3.14 ft^2

Hood height above furnace = 3 ft

Room air temperature = 100°F.

Problem:

Determine the minimum ventilation requirements for the furnace.

Table 74. HYDROSTATIC SCRUBBER DATA

Test	A	B	C	D	E	F
Total number of furnaces	2	1	1	2	1	1
Furnace size, tons	6 and 20	20	6	3 and 3	50	75
Process wt, lb/hr	12,444	4,720	6,240	5,020	27,200	43,900
Volume of gases inlet, scfm	17,500	22,700	20,700	10,140	25,900	32,400
Volume of gases outlet, scfm	20,600	24,600	20,700	10,860	29,800	35,600
Gas temperature inlet, °F	132	123	110	145	297	281
Gas temperature outlet, °F	89	76	92	92.5	99	105
Fume concentration inlet, gr/scf	0.158	0.0657	0.167	0.329	0.423	0.966
Fume concentration outlet, gr/scf	0.055	0.0441	0.102	0.108	0.109	0.551
Fume emission inlet, lb/hr	23.7	12.8	29.6	28.7	94	268
Fume emission outlet, lb/hr	9.71	9.3	13.2	10.1	27.8	168
Collection efficiency, %	59.1	27.3	55.4	65	70.4	37.3

Solution:

$q = 5.4\ A_s\ (m)^{1/3}\ (\Delta t)^{5/12}$ (from Chapter 3)

where

q = rate of thermal air motion at top of heat source, cfm

A_s = surface area of hot body and face area of hood, ft^2

m = diameter of crucible, ft. For lack of proved experimental values for m, the diameter of the molten metal (heat source) will be used in the operation

Δt = temperature differential between hot body and room air, °F

$$q = (5.4)(3.14)(2)^{1/3}(2,900)^{5/12}$$

$$q = 590 \text{ cfm}$$

The formula used in calculating the ventilation requirements is accurate only for low-canopy hoods having an area equal to that of the heat source and having a maximum height of approximately 3 feet above the furnace. For high-canopy hoods, the hood area and ventilation volume must be increased.

Air Pollution Control Equipment

The design considerations for the remainder of the control system, including ductwork, type of collector, and fan and motor selection, are the same as outlined for electric-arc furnaces. Figure 178 is a photograph of two induction furnaces served by a canopy-type hood that vents to a baghouse.

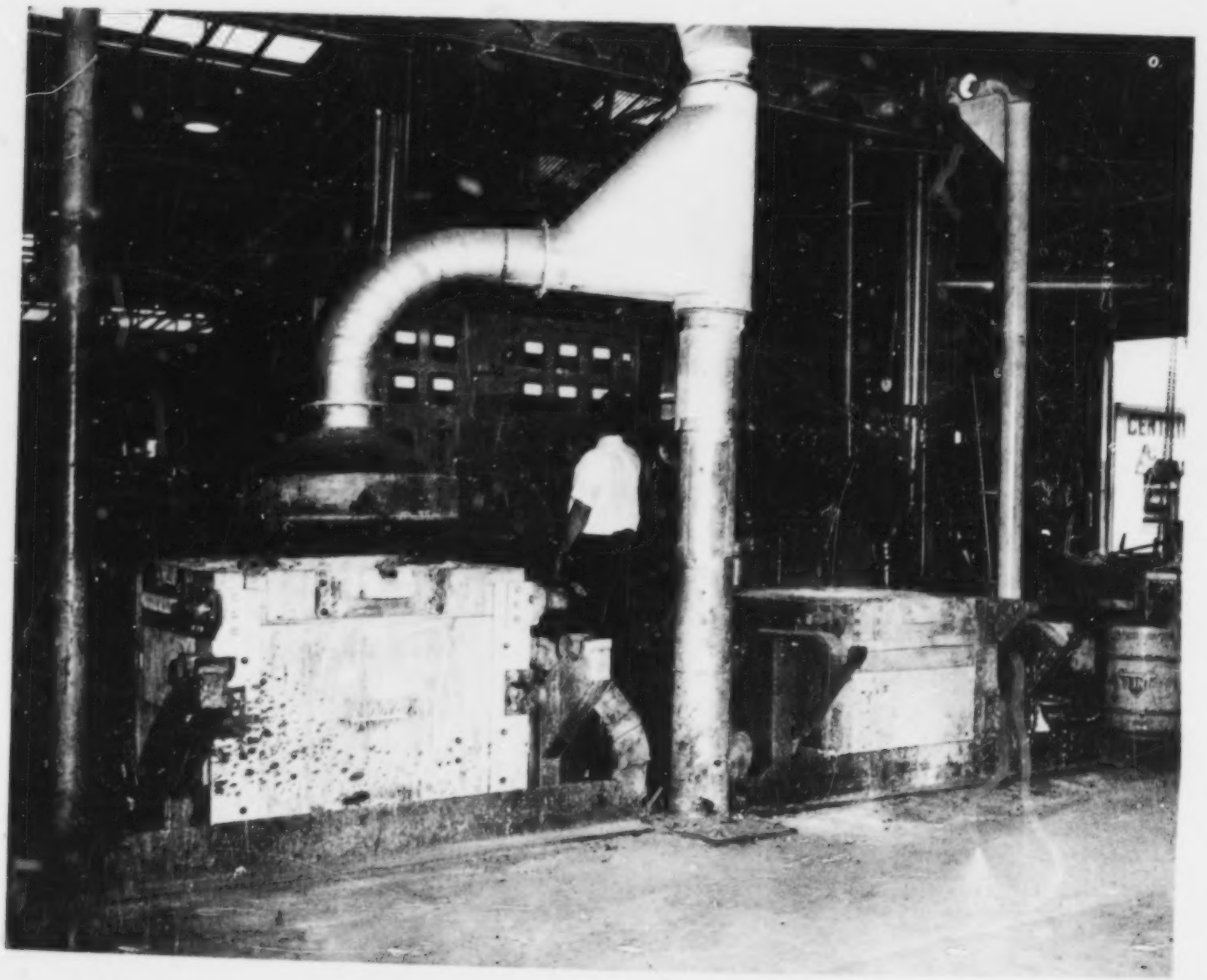


Figure 178. Canopy-type hood serving two electric-induction furnaces (Centrifugal Casting, Long Beach Calif.).

IRON CASTING

Control of the air pollution that results from the melting and casting of iron may be conveniently considered according to the type of furnace employed. The cupola, electric, and reverberatory furnaces are the types most widely encountered. The air pollutants are similar, regardless of the furnace used; the primary differences among the air pollution control systems of the various furnace types are to be found in the variations in hooding, and the necessary preparation and treatment of the contaminated gases from the furnaces. Essentially, the air pollution problem becomes one of entraining the smoke, dust, and fumes at the furnace and transporting these contaminants to suitable collectors.

CUPOLA FURNACES

The most widely encountered piece of equipment in the gray iron industry is the cupola furnace. High production rates are possible and production costs per ton of metal are relatively low. Despite this, where the product permits, some gray iron foundries have substituted reverberatory furnaces for their cupolas rather than install the air pollution control equipment that cupolas require. Table 75 shows one manufacturer's recommendations for operating cupolas.

The Air Pollution Problem

Air contaminants emitted from cupola furnaces are (1) gases, (2) dust and fumes, and (3) smoke and oil vapor. The following is a typical cupola combustion gas analysis: Carbon dioxide, 12.2 percent; carbon monoxide, 11.2 percent; oxygen, 0.4 percent; nitrogen, 76.2 percent. Twenty to thirty percent by weight of the fumes are less than 5 microns in size. A particle size analysis of the dust and fumes collected from gray iron cupolas is shown in Table 76, as are some emission rates. Tables 77 and 78 show micromerograph and spectrographic particle size analysis of two samples taken from the hoppers of a bag filter serving a gray iron cupola furnace. Dust in the discharge gases arises from dirt on the metal charge and from fines in the coke and limestone charge. Smoke and oil vapor arise primarily from the partial combustion and distillation of oil from greasy scrap charged to the furnace.

Hooding and Ventilation Requirements

One way to capture the contaminants discharged from a cupola furnace is to seal the cupola top and vent all the gases to a control system. A second method is to provide a vent in the side of the cupola a few feet below the top of the burden and vent the gases to a control system. The control system consists of an afterburner, a gas-cooling device, and a dust collector, which is either a baghouse or an electrical precipitator. The system must be designed to exhaust enough gas volume to remove all the products of combustion from the cupola and to inspirate sufficient air at the charge opening to prevent cupola gas discharge at that point. In addition, the exhaust gas volume must be sufficient to remove the products of combustion from the afterburner section. In cupolas of large diameter (over 36 in.), enclosure of the charge opening with refractory-lined or water-cooled doors is usually necessary. These doors are pneumatically operated to open only during the actual dumping of a charge into the cupola.

Even though a closed top cupola is equipped with a door to cover the charge opening, it is common practice to design the ventilation unit to provide at least 250 fpm average indraft velocity across the full open area of the charge opening.

Air Pollution Control Equipment

Collection efficiencies of several small-scale control devices on gray iron cupolas are shown in Table 79. These tests indicate the superior efficiencies of baghouses and electrical precipitators and, in practice, only these devices have been found to operate satisfactorily in Los Angeles County. As mentioned, these systems also include auxiliary items such as afterburners, gas-cooling devices, and settling chambers.

Afterburners

An afterburner is generally installed in a cupola furnace control system for two reasons. The high carbon monoxide content of the cupola effluent presents a definite explosion hazard; this hazard can be avoided by burning the carbon monoxide to carbon dioxide. Secondly, the afterburner burns combustion particulates, such as coke breeze and any smoke and oil vapors that may be distilled from the furnace charge. This combustion of oil vapors prevents later condensation on the surface of the filter bags and their resultant blinding. While afterburners may be installed as separate units, the common practice is to use the upper portion of the cupola between the charging door and the cupola top as the afterburner. When this is done, the height of the standard cupola must usually be increased to give a volume sufficient to provide adequate residence time to complete the combustion in the afterburner. As described earlier, the pollution problem from the various iron processes originates from emission of gases, dust, fumes, and smoke. The ratios of the quantities of the contaminants emitted from this equipment vary appreciably and influence the selection of the control device or devices to be employed.

Table 75. GENERAL RECOMMENDATIONS FOR OPERATING WHITING CUPOLAS
(Practical Hints on Cupola Operation, No. 237-R, Whiting Corporation, Harvey, Illinois)

Cupola size	Shell diameter, in.	Min. thickness of lower lining, in.	Diameter inside lining, in.[a]	Area inside lining, in.^{2}	Melting rate, tons/hr, with iron-coke (after bed) ratios of				Bed coke height above tuyeres,[b] in.	Coke and iron charges, lb					Limestone, lb	Air through tuyeres, cfm	Suggested blower selection[c]	
					6	8	10	12		Coke	Iron 6/1	Iron 8/1	Iron 10/1	Iron 12/1			cfm	Discharge pressure, oz
0	27	4-1/2	18	254	3/4	1			28 to 44	20	120	160			4	570	640	8
1	32	4-1/2	23	415	1	1-1/2			36 to 42	35	210	280			7	940	1,040	16
2	36	4-1/2	27	572	1-3/4	2-1/4			36 to 42	45	270	360			9	1,290	1,430	16
2-1/2	41	7	27	572	1-3/4	2-1/4			36 to 42	45	270	360			9	1,290	1,430	16
3	46	7	32	804	2-1/2	3-1/4	4		40 to 46	65	390	520	650		13	1,810	2,000	16
3-1/2	51	7	37	1,075	3-1/4	4-1/4	5-1/4		40 to 46	85	510	680	850		17	2,420	2,700	16 to 20
4	56	7	42	1,385	4	5-1/2	7		42 to 48	110	660	880	1,110		22	3,100	3,450	20 to 24
5	63	9	45	1,590	4-1/2	6-1/4	8		42 to 48	130	780	1,040	1,300		26	3,600	4,000	20 to 24
6	66	9	48	1,809	5-1/2	7-1/4	9	10-3/4	45 to 51	145	870	1,170	1,450	1,740	29	4,100	4,500	24 to 28
7	72	9	54	2,290	7	9-1/4	11-1/2	13-3/4	45 to 51	185	1,100	1,480	1,850	2,220	37	5,200	5,750	24 to 32
8	76	9	60	2,827	9	11-1/4	14	17	45 to 51	225	1,350	1,800	2,250	2,700	45	6,400	7,100	24 to 32
9	84	9	66	3,421	10-1/2	13-3/4	17	20-1/2	45 to 51	275	1,650	2,200	2,750	3,300	55	7,700	8,600	24 to 32
9-1/2	90	9	72	4,071	12-1/4	16-1/4	20-1/4	24-1/2	47 to 53	325	1,950	2,600	3,250	3,900	65	9,200	10,200	28 to 36
10	96		78	4,778	15	19	23-3/4	28-3/4	47 to 53	385	2,300	3,080	3,850	4,600	77	10,700	11,900	28 to 36
11	102	12	78	4,778	15	19	23-3/4	28-3/4	47 to 53	385	2,300	3,080	3,850	4,600	77	10,700	11,900	28 to 40
12	108	12	84	5,542	17	22-1/4	27-3/4	33-1/4	47 to 53	445	2,670	3,560	4,450	5,400	89	12,500	13,900	32 to 40

[a]For long heats, use heavier linings.
[b]Height of bed coke varies as square root of blast pressure. Recommend blowers with 20-oz discharge pressure when air weight control is used.
[c]Additional pressure capacity may be requried when auxiliary equipment is added to the blast systems or when piping is long or complicated.

Table 76. DUST AND FUME EMISSIONS FROM GRAY IRON CUPOLAS

Test No.	1	2	3	4	5	6	7
Cupola data							
Inside diameter, in.	60	37	63	56	42	60	48
Tuyere air, scfm	-	1,950	7,500	-	-	-	-
Iron-coke ratio	7/1	6.66/1	10.1/1	6.5/1	9.2/1	9.6/1	7.4/1
Process wt, lb/hr	8,200	8,380	39,100	24,650	14,000	36,900	16,800
Stack gas data							
Volume, scfm	8,300	5,520	30,500	17,700	20,300	21,000	8,430
Temperature, °F	1,085	1,400	213	210	430	222	482
CO_2, %	-	12.3	2.8	4.7	5.2	-	-
O_2, %	-	-	-	12.7	11.8	-	-
CO, %	-	-	-	0	0.1	-	-
N_2, %	-	-	-	67.5	67.3	-	-
Dust and fume data							
Type of control equipment	None	None	None	Baghouse	Elec precip afterburner	Baghouse	Elec Precip
Concentration, gr/scf							
Inlet	-	-	-	1.33	2.973	0.392	1.522
Outlet	0.913	1.32	0.413	0.051	0.0359	0.0456	0.186
Dust emission, lb/hr							
Inlet	-	-	-	197	184.7	70.6	110
Outlet	65	62.4	108	7.7	6.24	8.2	13.2
Control efficiency, %	-	-	-	96	96.6	88.4	87.7
Particle size, wt %							
0 to 5 μ	18.1	17.2	23.6	25.8	-	-	-
5 to 10 μ	6.8	8.5	4.5	6.3	-	-	-
10 to 20 μ	12.8	10.1	4.8	2.2	-	-	-
20 to 44 μ	32.9	17.3	9.5	10.0[a]	-	-	-
> 44 μ	29.3	46.9	57.9	55.7[b]	-	-	-
Specific gravity	3.34	2.78					

[a]From 20 to 50 μ.
[b]Greater than 50 μ.

An afterburner should be designed with heat capacity to raise the temperature of the combustibles, inspirated air, and cupola gases to at least 1,200°F. The geometry of the secondary combustion zone should be such that the products to be incinerated have a retention time of at least 1/4 second. A luminous flame burner is desirable, since it presents more flame exposure. Enough turbulence must be created in the gas stream for thorough mixing of combustibles and air. In large-diameter cupola furnaces, stratification of the gas stream may make this a major problem. One device, proved successful in promoting mixing in large-diameter cupolas, is the inverted cone shown in Figure 179. The combustion air is inspirated through the charging door and, if necessary, may also be inspirated through openings strategically located in the cupola circumference, above the charging opening. The rapid ignition of the combustible effluent by the afterburner frequently results in a pulsating or puffing emission discharge from the charging door. This can be eliminated by the installation of an ignition burner below the level of the charging door, which ignites and partially burns the combustible effluent.

A cupola afterburner need not be operated through the entire furnace cycle. Even without an afterburner, an active flame can be maintained in the upper portion of the cupola. This requires control of the materials charged, and likewise, control of combustion air and mixing. The afterburner must, however, be in operation during the furnace light-off procedure. It is desirable to ignite the coke bed with gas torches, because considerable smoke may result if the light-off is done with kindling wood.

Baghouse dust collectors

The temperature of the gas stream discharged from the top of a cupola may be as high as 2,200°F. If a baghouse is used as a control device, these gases must be cooled to prevent burning or scorching of the cloth bags. Maximum temperatures allowed vary from 180°F for cotton bags to 500°F for glass fabric bags.

Cooling can be effected by radiant cooling columns, evaporative water coolers, or by dilution with ambient air. Figure 180 shows an installation in which the gas stream is cooled by dilution and ra-

Table 77. MICROMEROGRAPH PARTICLE SIZE ANALYSIS OF TWO SAMPLES TAKEN FROM A BAGHOUSE SERVING A GRAY IRON CUPOLA FURNACE

Sample A		Sample B	
Equivalent particle diameter, μ	Cumulative wt %	Equivalent particle diameter, μ	Cumulative wt %
0.9	0.0	1.0	0.0
1.1	1.3	1.3	1.7
1.4	3.4	1.6	3.6
1.8	7.4	2.1	7.0
2.3	11.6	2.6	10.5
2.8	15.0	3.0	13.3
3.7	20.4	4.2	19.9
4.6	24.6	5.2	24.8
5.5	27.3	6.3	29.0
6.4	29.0	7.3	32.5
6.9	29.8	7.8	34.9
7.3	30.3	8.4	36.3
7.8	30.7	8.9	38.6
8.2	31.2	9.4	39.8
8.7	31.3	10.1	41.1
9.3	31.9	10.4	42.0
10.1	32.1	10.9	43.2
11.0	33.1	12.5	45.4
12.4	33.5	14.1	46.7
13.7	33.6	15.6	47.0
16.5	33.9	18.8	47.4
19.3	34.2	21.9	47.6
22.0	34.4	25	47.7
24.7	34.7	28.1	48.0
27.5	35.1	31.3	48.4
30.2	36.0	34.4	48.8
34.4	37.5	39.1	49.8
41.3	40.6	46.9	52.3
55.0	46.4	62.5	56.7
68.7	51.1	78.1	63.4
82.6	55.9	93.8	69.3
123	61.4	148	80.5

Table 78. QUALITATIVE SPECTROGRAPHIC ANALYSIS OF TWO SAMPLES TAKEN FROM A BAGHOUSE SERVING A GRAY IRON CUPOLA FURNACE[a]

Element	Approx amount, %	Approx amount, %
	Sample A	Sample B
Aluminum	0.81	1.1
Antimony	0.24	0.24
Boron	0.050	0.054
Cadmium	0.13	0.064
Calcium	0.16	0.25
Chromium	0.022	0.019
Copper	0.42	0.32
Gallium	0.017	0.019
Germanium	0.018	0.015
Iron	6.0	7.5
Lead	17.0	17.0
Magnesium	0.29	0.30
Manganese	1.0	0.81
Molybdenum	0.0068	0.0075
Nickel	0.023	0.022
Potassium	1.5	1.2
Silicon	8.6	15.0
Silver	0.0093	0.0089
Tin	0.41	0.38
Titanium	0.019	0.034
Zinc	7.1	5.9

[a] These data are qualitative only and require supplementary quantitative analysis for actual amounts of the elements found to be present. These are the same samples as given in Table 77.

Table 79. SOME COLLECTION EFFICIENCIES OF EXPERIMENTAL SMALL-SCALE CONTROL DEVICES TESTED ON GRAY IRON CUPOLAS[a]

Equipment tested	Inlet gas volume, scfm	Outlet gas volume, scfm	Inlet dust load, gr/scf	Outlet dust load, gr/scf	Collection efficiency, %	Remarks
Controls for cupolas[b]						
High-efficiency cyclone	330	384	1.225	0.826	22.5	
Dynamic water scrubber	1,410	1,760	1.06	0.522	38.2	Water added before control unit for cooling totalled 6 gpm
Venturi-type scrubber	375	432	1.17	0.291	71.3	Two gpm-water introduced for cooling gas stream; 3.5 gpm added at venturi throat; cyclonic scrubber operated dry
Dynamic--impingement wet scrubber	605	995	0.95	0.141	75.6	Water rate in excess of 10 gpm
Baghouse--one silicone-treated glass wool bag, 10 in. dia x 10 ft length	52.7	52.7	1.32	0.046	96.5	Average temp, 372°F; average filtering velocity, 3.22 gpm
Evaporative cooler and redwood pipe electrical precipitator	1,160	1,330	1.263	0.0289	97.7	Water rate to cooler, 22 gpm; to precipitator, 2 gpm
Other basic equipment						
Natural gas-fired reverberatory furnace	--	5,160	--	0.00298	96.2[c]	Melting rate, 546 lb/hr; gas consumption rate, 4,200 cfh; melting clean scrap and pig iron

[a] In all cases, equipment was installed and operated according to the manufacturer's recommendations.
[b] The six control devices were tested on the same cupola.
[c] This is not an actual collection efficiency, but a percent reduction when compared with average cupola emissions.

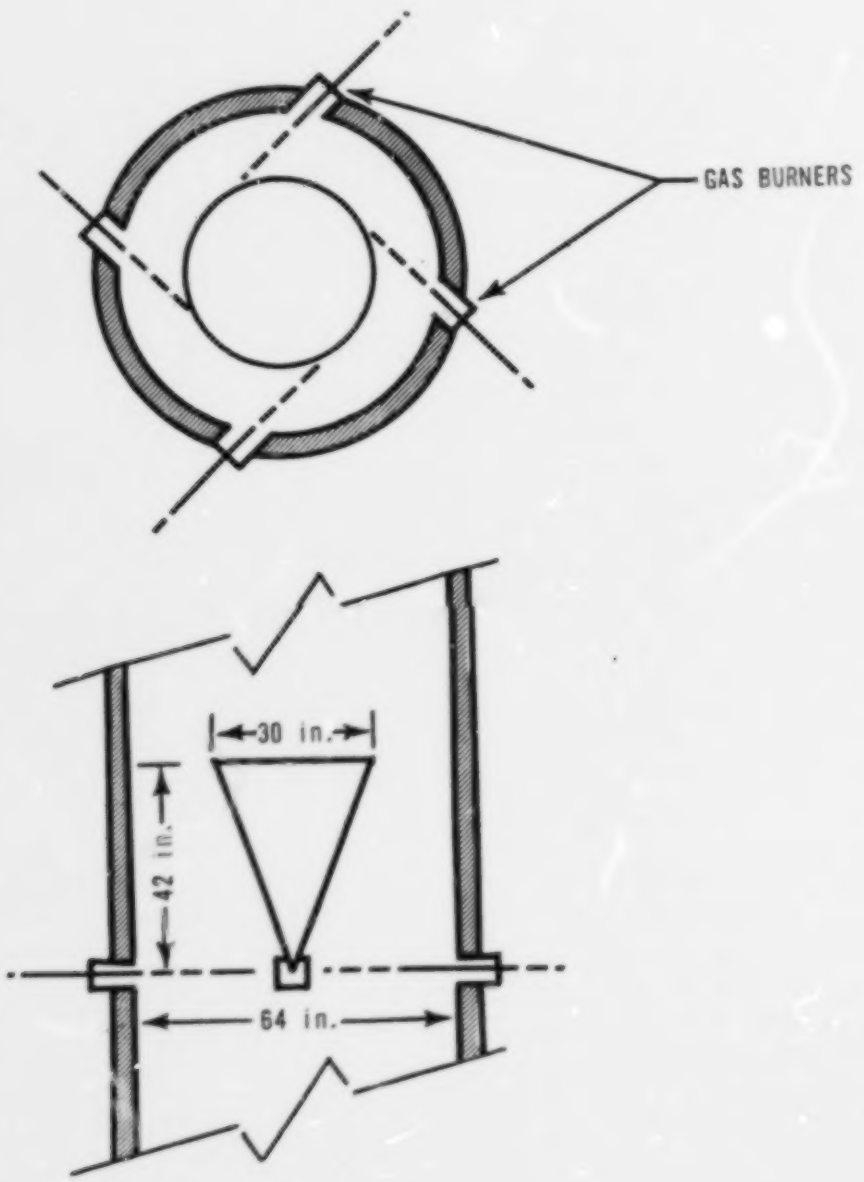


Figure 179. Integral afterburner with inverted cone installed in top part of cupola to create turbulence to ensure complete combustion.

diation-convection cooling columns. Of the three types of coolers, spraying is the most common. All types have been discussed in Chapter 3.

For satisfactory baghouse operation, when metallurgical fumes are to be collected, filtering velocity should not exceed 2-1/2 fpm. Provisions for cleaning collected material from the bags usually require compartmentation of the baghouse so that one section of the baghouse may be isolated and the bags shaken while the remainder of the system is in operation. The gas temperature through the baghouse should not be allowed to fall below the dew point, because condensation within the baghouse may cause the particles on the bag surfaces to agglomerate, deteriorate the cloth, and corrode the baghouse enclosure. A bypass control must also be installed. If the cooling system fails, the bypass is opened, which discharges the effluent gas stream to the atmosphere and thus prevents damage to the bags from excessive temperatures. Properly designed and maintained baghouses can normally be expected to have efficiencies ranging upwards from 95 percent.

Electrical precipitators

Electrical precipitators are an efficient control device for collecting most metallurgical fumes where steady-state conditions of temperature and humidity can be maintained in the gases to be cleaned. The procedures used in determining the effluent gas volume and temperatures for a precipitator control system are the same as those for a baghouse control system. The collection efficiency

of an electrical precipitator depends in part upon the apparent resistivity of the material to be collected. This, in turn, depends upon the characteristics of the material, and the moisture content and temperature of the effluent gas stream. After the condition of the gas stream under which precipitation is to take place has been determined, the system's conditioning units for controlling the temperature and humidity of the effluent gas stream can be designed. The large temperature fluctuations of the effluent gas stream from a cupola require that the control system be designed to main-

Figure 180. Cupola controlled by radiation convection coolers and baghouse (Alhambra Foundry Company, Alhambra, Calif.).

Cupola data

Size, 45-in. ID	Iron - coke ratio, 8:1
Flue gas vol, 7,980 scfm	Flue gas temp, 1,875° to 2,150°F
Tuyere air, 3,450 scfm	Charging rate, 20,200 lb/hr

Gas conditioner data

Radiation and convection type	Gas vol (incl recirculation), 16,100 scfm
Cooling area, 10,980 ft^2	Size, 16 col 42-in. dia x 42-in. H
Log mean temp diff, 670°F	Inlet gas temp, 1,030°F
Heat trans coef, 1.59 Btu/hr-ft^2 per°F	Outlet gas temp, 404°F

Baghouse data

Tubular and compartmented type	Collection efficiency, 99+%
Inlet gas volume, 13,100 cfm	Tube size, 11-in. dia x 180-in. L
Filter area, 4,835 ft^2	Inlet gas temp, 404°F
Filter media, silicone glass	Filtering velocity, 2.7 fpm
Shaking cycle, 90 min (manual by compartment)	Pressure drop, 3 to 4 in. WC

tain proper levels of temperature and humidity. Installation and operation of equipment to maintain these levels may be bulky and expensive, and should be reviewed with the manufacturer. In order to avoid corrosion in the precipitator unit, the control system must be designed to prevent water carryover or condensation. Figure 181 shows a cylindrical water spray conditioning cham-

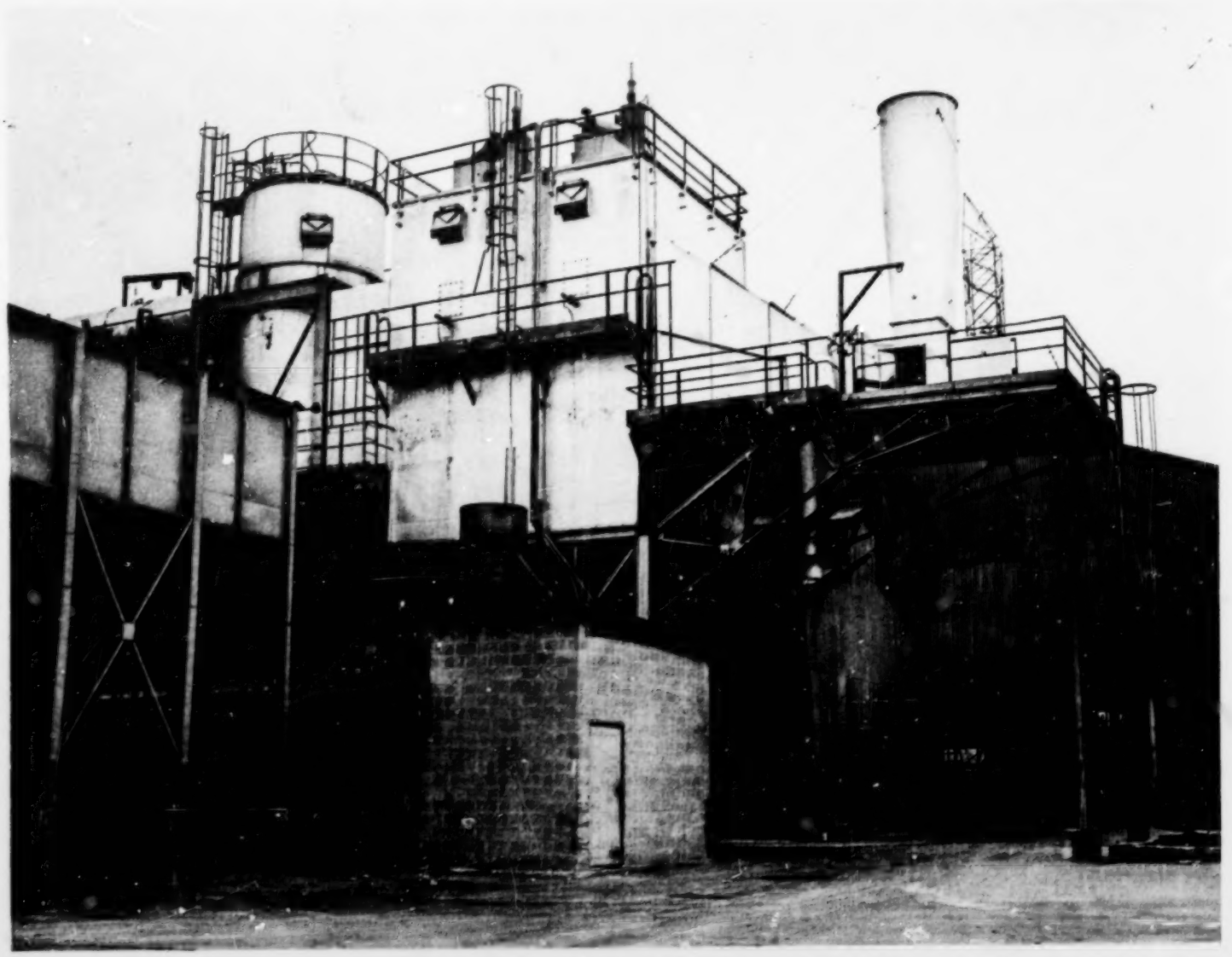


Figure 181. Photograph of an electrical precipitator preceded by a water spray conditioning chamber; vented cupola and afterburner not shown (Alabama Pipe Company, Southgate, Calif.).

Cupola data

Size, 42-in. ID	Flue gas temp, 400° to 1,400°F
Flue gas vol, 8,700 scfm	Iron - coke ratio, 9.2:1
Tuyere air, 3,000 cfm	Charging rate, 14,000 lb/hr

Afterburner data

Type of structure--an unused cupola furnace converted by the installation of four premix gas burners with full modulating temperature controls to maintain 1,100°F minimum outlet temperature. Fuel input, 10 million Btu/hr maximum

Gas conditioner data

Evaporator cooler type	Gas temp inlet, 1,100°F min.
Water rate, 75 gpm (max)	Size, 10-ft 6-in. dia x 23-ft 6-in. length

Electrical precipitator data

Type, expanded metal	No. of sections, 2 in series
Collecting electrode, size, 17 ft 6 in. x 4 ft 6 in.	Size, 23 ducts 8-3/4 in. x 17 ft 6 in. x 9 ft
Discharge electrode, 0.109-in. dia	Average gas temp, 430°F
Gas volume, 20,300 scfm	% Moisture in flue gas, 15%
Outlet dust loss, 0.0359 gr/scf	Overall efficiency, 96.6

ber, upper left; electrical precipitator, center; fan and discharge duct, upper right. These control units vent a cupola with a separate afterburner, not shown in the photograph. The precipitator rectifier is housed in the concrete block building in the foreground.

Additional design information on electrical precipitators has been presented in Chapter 4.

Illustrative Problem

The following example shows some of the factors that must be considered in designing a control system for a gray iron cupola furnace.

Example 27

Given:

A 32-in.-ID cupola

Charging door area, 4.5 ft^2

Tuyere air, 1,810 scfm

Maximum gas temperature at cupola outlet, 2,000°F

Minimum incineration temperature to be maintained at cupola outlet, 1,200°F.

Assume a closely coupled unit from the cupola to the evaporative cooling chamber and an insulated duct between the evaporative cooling chamber and the baghouse.

Assume the effluent gases have the same properties as air. (Consideration of the enthalpies and specific heats of the gaseous constituents in the effluent gas stream will show that this is an accurate assumption. Any corrections would introduce an insignificant refinement to the calculations when considered with respect to the accuracy of other design factors.)

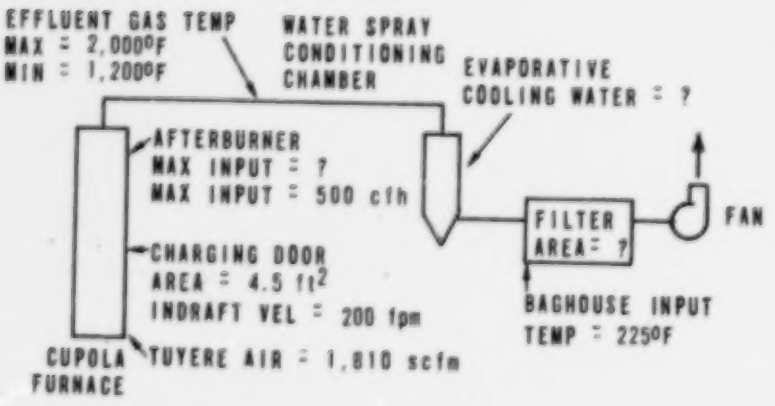


Figure 182. Control system for a gray iron cupola furnace.

Problem:

Determine the design features of an evaporative cooling system and a baghouse to serve the cupola.

Solution:

1. Volume of gases from tuyeres = 1,810 scfm or 139.3 lb/min

2. Heat required from afterburner to raise temperature of tuyere air products of combustion from an assumed low of 500°F to a minimum incineration temperature of 1,200°F:

Enthalpy of gas (1,200°F) = 287.2 Btu/lb (see Table D3 in Appendix D)

Enthalpy of gas (500°F) = 106.7 Btu/lb
Δh = 180.5

(139.3)(180.5) = 25,150 Btu/min

3. Heat required from afterburner to raise charging door indraft air from 60° to 1,200°F:

Assume a charging door indraft velocity of 200 fpm, which will be adequate to ensure an indraft of air at all times.

Charge door indraft volume = (4.5)(200) = 900 scfm or 69.3 lb/min

Enthalpy of gas (1,200°F) = 287.2 Btu/lb

Enthalpy of gas (60°F) = 0
Δh = 287.2

(69.3)(287.2) = 19,900 Btu/min

4. Total heat to be supplied by afterburner:

Heat to tuyere air	= 25,150 Btu/min
Heat to charge door indraft volume	= 19,900 Btu/min
Total	45,050 Btu/min

5. Required natural gas volume capacity of afterburner to supply 45,050 Btu/min:

Heating value of gas = 1,100 Btu/ft^3

Heat available at 1,200°F, from the burning of 1 ft^3 of gas with theoretical air = 721.3 Btu/ft^3 (see Table D7 in Appendix D)

$$\frac{45,050}{721.3} = 62.4 \text{ cfm}$$

6. Volume of products of combustion from afterburner:

With theoretical air, 1 ft^3 of gas yields 11.45 ft^3 of products of combustion (see Table D7 in Appendix D)

$$(62.4)(11.45) = 715 \text{ cfm}$$

7. Total volume of products to be vented from cupola, scfm:

Volume from tuyere air = 1,810

Volume for charge door indraft = 900

Volume from afterburner = 715

3,425 scfm

or 264 lb/min

8. Volume of vented gases at 1,200°F:

$$(3,425)\left(\frac{1,200 + 460}{60 + 460}\right) = 10,900 \text{ cfm}$$

9. Duct diameter from cupola exit to evaporative chamber:

Use design velocity of 3,500 fpm

Duct cross-sectional area = $\frac{10,900}{3,500} = 3.12 \text{ ft}^2$

∴ Use 24-in.-dia. duct

10. Cooling required to reduce temperature of vented products from cupola from 1,200° to 225°F:

Baghouse inlet design temperature taken as 225°F

Enthalpy of gas at 1,200°F = 287.2 Btu/lb
Enthalpy of gas at 225°F = 39.6 Btu/lb

Δh = 247.6 Btu/lb

$$(264)(247.6) = 65,300 \text{ Btu/min}$$

11. Water to be evaporated to cool vented gas products from 1,200° to 225°F:

Heat absorbed per lb of water:

$$Q = h_g \text{ (225°F, 14.7 psia)} - h_f \text{ (60°F)}$$

$$= 1,156.8 - 28.06 = 1,128.74 \text{ Btu/lb } H_2O$$

$$\frac{65,300}{1,128.74} = 58.0 \text{ lb } H_2O/\text{min}$$

12. Volume of evaporated cooling water at 225°F:

v = 27.36 ft^3/lb H_2O (14.7 psia, 225°F)

$$(58.0)(27.36) = 1,586 \text{ cfm}$$

13. Total volume of products vented from spray chamber:

Volume of products from cupola = 3,425 scfm

Volume of evaporated cooling water = 1,586 cfm (225°F)

$$(3,425)\left(\frac{225 + 460}{60 + 460}\right) + 1,586 = 6,106 \text{ cfm}$$

14. Duct diameter between spray chamber and baghouse:

Use design velocity of 3,500 fpm

$$\frac{6,106}{3,500} = 1.745 \text{ ft}^2$$

∴ Use an 18-in.-dia. duct

15. Required filter area of baghouse:

Design for a filtering velocity of 2 fpm

$$\frac{6,106}{2} = 3,053 \text{ ft}^2$$

During burndown, the cupola discharge gases will increase in temperature to 2,000°F and the afterburner input will be reduced to the low fire settling at an input of 500 ft^3 of gas per hr (8.33 cfm). Calculations will be made under this new operating condition to determine whether the previously calculated values for duct sizes, evaporative water quantity, and filter area are compatible.

16. Volume of products of combustion from afterburner:

$$(8.33)(11.45) = 95.5 \text{ cfm}$$

17. Total volume of products to be vented from cupola:

Volume from tuyere air = 1,810
Volume from charge door indraft = 900
Volume from afterburner = 95.5

2,805.5 scfm

or 216 lb/min

18. Volume of vented gases at 2,000°F:

$$(2,805.5)\left(\frac{2,000 + 460}{60 + 460}\right) = 13,280 \text{ cfm}$$

19. Gas velocity between cupola and spray chamber when using 24-in. duct from calculation 9:

$$\frac{13,280}{3.142} = 4,230 \text{ fpm}$$

Velocity is greater than necessary but not excessive.

20. Cooling required to reduce temperature of vented products from cupola from 2,000° to 225°F:

Enthalpy of gas at 2,000°F = 509.5 Btu/lb
Enthalpy of gas at 225°F = 39.6 Btu/lb

Δh = 469.9 Btu/lb

$$(216)(469.9) = 101,300 \text{ Btu/min}$$

21. Water to be evaporated to cool vented gas products from 2,000° to 225°F:

Heat absorbed per lb of water = 1,128.74 Btu/lb (see calculation 11)

$$\frac{101,300}{1,128.74} = 90 \text{ lb } H_2O/\text{min}$$

This is greater than that determined in calculation 11 and must therefore be taken as the design value.

22. Volume of evaporated cooling water at 225°F:

v = 27.36 ft^3/lb H_2O (14.7 psia, 225°F)

$$(90)(27.36) = 2,460 \text{ cfm}$$

23. Total volume of products vented from spray chamber:

Volume of products from cupola = 2,805.5 scfm
Volume of evaporated cooling water = 2,460 cfm (225°F)

$$(2,805.5)\left(\frac{225 + 460}{60 + 460}\right) + 2,460 = 6,160 \text{ ft}^3$$

24. Gas velocity between spray chamber and baghouse using 18-in. duct from calculation 14:

$$\frac{6,160}{1.767} = 3,480 \text{ cfm}$$

Velocity is comparable with design value of 3,500 fpm

25. Filtering velocity using filter area from calculation 15:

$$\frac{6,160}{3,053} = 2.02 \text{ fpm}$$

This ratio is in agreement with a filtering velocity of 2 fpm

26. The exhaust system and fan calculations are made as outlined in Chapter 3. After a system resistance curve has been calculated and plotted, a fan is selected whose characteristic curve will intersect the system curve at the required air volume, which for this example would be 6,160 cfm.

Problem note: This example problem illustrates typical calculations that can be followed in designing a cupola control system. Each installation must be evaluated separately, considering expected maximum and minimum temperatures, gas volumes, duct lengths, and so forth. For example, this problem was patterned after a small cupola where the charging door remains open. For large cupolas, opening and closing the charging doors must be evaluated relative to its effect upon gas volumes and temperatures. If duct runs are long, the radiation-convection losses may be worth considering. The sizing of the fan motor depends upon the weight of gas moved per unit time. This in turn depends upon the density (considering air, water vapor, and temperature) of the gas stream. These items are taken into consideration in making the exhaust system resistance calculations. It may be necessary to reduce the system's airflow by dampering in order to prevent overloading of the fan motor when making a cold startup under ambient conditions. See Chapter 3 for design parameters for cooling of effluent gas stream with radiation-convection cooling columns. Since the temperature of the effluent gas stream from the cupola will fall in the range of 1,200° to 2,000°F, the duct connecting the cupola and water spray conditioning chamber should be made of stainless steel or be refractory lined.

ELECTRIC-ARC FURNACES

Electric-arc furnaces are commonly used in the secondary melting of iron where special alloys are to be made. These furnaces may be either the direct- or indirect-arc type. Pig iron and scrap iron are charged to the furnace and melted, and alloying elements and fluxes are added at specified intervals. These furnaces have the advantage of rapid and accurate heat control.

The Air Pollution Problem

Since no gases are used in the heating process, some undesirable effects on the metal are eliminated. Since arc furnaces in the iron industry are virtually always used to prepare special alloy irons, the quality of the material charged is closely controlled. The charging of greasy scrap, which would emit combustible air contaminants, would only needlessly complicate the alloying procedure. Afterburners are, therefore, rarely required in conjunction with arc furnace operations. The emissions consist, primarily, of metallurgical fumes and can be controlled by either a baghouse or an electrical precipitator. The emission rates from electric-arc furnaces vary according to the process from 5 to 10 pounds per ton of metal processed.

Hooding and Ventilation Requirements

Direct-arc furnaces for melting gray iron present a unique and difficult problem of hooding. The hood's geometry and the indraft velocity must be designed to ensure virtually complete collection of the emissions from the furnace. Hood design varies considerably for different furnaces. Furnaces are most successfully hooded by building the hood into the cover or top of the furnace. This, of course, means designing an air chamber or compartment above the furnace roof and providing a duct connection to the chamber so that the collected contaminants may be vented to the control device. Since direct-arc furnaces receive only a limited use for melting cast iron, generalizing about the ventilation requriements is difficult; however, 5,000 to 7,500 cfm per ton of production apparently yields a reasonable degree of dust and fume capture. To be most effective, the ventilation air exhausted from the furnace should also be available to the furnace hood during periods of tapping and charging the furnace. This means that some type of telescoping ductwork or slip-connection ductwork must form the connection between the control device and the hood. Figure 183 illustrates an adjustable-type hood used with a baghouse venting rocking-arc furnaces. The hood is positioned by means of a telescoping connection that is mechanically controlled. In the right foreground of the photograph, the hood is shown lowered into position with the furnace in operation, while in the left background, the hood is shown raised from the furnace to facilitate charging and furnace access.

Air Pollution Control Equipment

Baghouse dust collectors

Elaborate facilities for cooling the effluent gas stream from an electric furnace may not be necessary for two reasons: (1) No products of combustion result from the burning of fuel, and (2) canopy-type or roof-type hoods are generally used. Thus, the volume of the effluent gas stream is low, and the ventilation air drawn in at the hood provides cooling. As with cupola baghouses, a filtering velocity of 2-1/2 fpm should not be exceeded and a shaking mechanism and compartmentation must be provided.

Electrical precipitators

As in the case of baghouse dust collectors serving electric-arc furnaces, no elaborate facilities are necessary for cooling the effluent gas stream from an electric furnace vented to an electrical precipitator, though the design humidity and temperature of gases entering the electrical precipitator must be met. This may require water spray sections or afterburner devices to heat and humidify the gases vented to the precipitator.

INDUCTION FURNACES

Core-type electric-induction furnaces are also used for melting cast iron. In this type of furnace, alternating current is passed through a primary coil with a solid iron core. The molten iron contained within a loop that surrounds the primary coil acts as the secondary. The alternating current that flows through the primary induces a current in the loop, and the electrical resistance of the molten metal creates the heat for melting. The heated metal circulates to the main furnace chamber and is replaced by cooler metal. This circulation results in uniform metal temperature and alloy composition.

The electric-induction furnace generates considerably smaller amounts of air contaminants than the cupola or electric-arc furnace does; the amount is mainly dependent upon the condition of the metal charged. When pig iron and clean casting returns are charged, no air pollution control equipment is necessary for ordinary melting. Contaminated scrap or the addition of magnesium for manufacturing ductile iron would, however, necessitate air pollution control equipment. In cases such as these, design requirements for a baghouse control system with canopy-type hooding are the same as later described in this chapter for coreless induction furnaces for steel melting.

REVERBERATORY FURNACES

Small reverberatory furnaces are also used in preparing gray and white cast iron alloys. If clean metal is charged to these furnaces, no excessive air pollution results from their use. Figure 184 shows a small, gas-fired, reverberatory

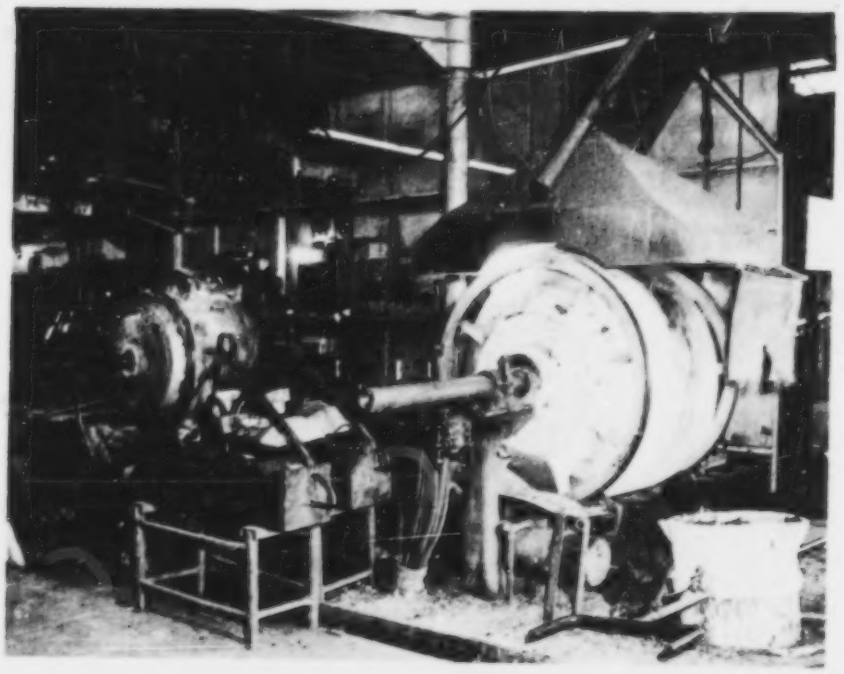


Figure 183. Rocking-arc furnaces venting through adjustable hoods to a baghouse (Centrifugal Casting Company, Long Beach, Calif.).

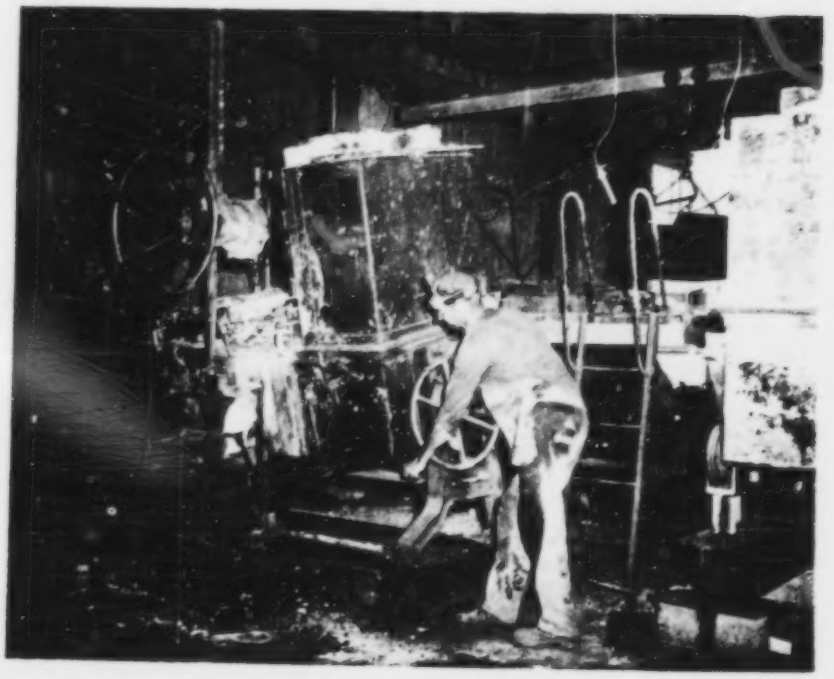


Figure 184. Gray iron reverberatory furnace (Pomona Foundry, Pomona, Calif.).

Reverberatory furnace data

Rated capacity, 1,000 lb
Fuel, natural gas
Furnace flue gases, calculated at 6,100 cfm at 2,850°F
Pouring temp, 2,700°F
Typical charge, 300 lb pig iron, 500 lb scrap iron, 200 lb foundry returns, 2 lb soda ash
Melting rate, 750 lb/hr
Fuel rate, 4,200 ft^3/hr

Test data

Gas volume at hood, 5,160 scfm
Dust loss in gr/scf, 0.00278
Average gas temp, 775°F
Loss in lb/hr, 0.13

furnace used in a gray iron foundry. Test results made upon a furnace of this type, rated at 1,000-pounds capacity, while it was melting clean scrap iron and pig iron, showed a particulate loss to the atmosphere of 0.00278 grain per standard cubic foot, or 0.14 pound per hour. Because of this low rate of particulate discharge, no air pollution control devices have been found necessary for the operations conducted in this type of furnace melting iron.

SECONDARY BRASS- AND BRONZE-MELTING PROCESSES

Copper when alloyed with zinz is usually termed brass, and when alloyed with tin is termed bronze. Other copper alloys are identified by the alloying metals such as aluminum bronze and silicon bronze. The true bronzes should not be confused with some other common classifications of bronzes, which are actually misnomers. For example, "commercial bronze" is a wrought red brass, and "manganese bronze" is a high-zinc brass. Because of high strength, workability, corrosion resistance, color, and other desirable physical characteristics, the copper-base alloys have found wide use for hardware, radiator cores, condensers, jewelry, musical instruments, plumbing fittings, electrical equipment, ship propellers, and many other devices.

The remelting of nearly pure copper and bronze does not have great interest from the standpoint of air pollution since only small amounts of metal are volatilized. This is due to the high boiling points of copper and tin (above 4,000°F) and their low normal pouring temperatures of about 2,000° to 2,200°F. With good melting practice, total emissions to the air should not exceed 0.5 percent of the process weight. The brasses containing 15 to 40 percent zinc, however, are poured at temperatures near their boiling points (about 2,200°F), and some vaporization or combustion of desirable elements, particularly zinc, is inevitable. Emissions into the air may vary from less than 0.5 percent to 6 percent or more of the total metal charge (St. John, 1955) and 2 to 15 percent of the zinc content through fuming (Allen et al., 1952), depending upon the composition of the alloy, the type of furnace used, and the melting practice.

FURNACE TYPES

Brass and bronze shapes for working, such as slabs and billets, are usually produced in large gas- and oil-fired furnaces of the reverberatory type. Most operators of secondary smelters also use this type of furnace for reclaiming and refining scrap metal, ordinarily casting the purified metal into pigs. Brasses and bronzes used to make commercial castings are usually melted in low-frequency induction furnaces in the larger foundries and in crucible-type, fuel-fired furnaces in the smaller job foundries. Electric furnaces, both arc and induction, are also used for castings. Generalizing in regard to the uses of various furnaces is difficult, since foundry practices are variable. A comparison of emissions from various types of furnaces is given in Table 80.

The Air Pollution Problem

Air contaminants emitted from brass furnaces consist of products of combustion from the fuel, and particulate matter in the form of dusts and metallic fumes. The particulate matter comprising the dust and fume load varies according to the fuel, alloy composition, melting temperature, type of furnace, and many operating factors. In addition to the ordinary solid particulate matter, such as fly ash, carbon, and mechanically produced dust, the furnace emissions generally contain fumes resulting from condensation and oxidation of the more volatile elements, including zinc, lead, and others.

As was previously mentioned, air pollution resulting from the volatilization of metals during the melting of nearly pure copper and bronze is not too serious because of the high boiling-point temperatures of copper, tin, nickel, aluminum, and even lead commonly used in these alloys. Alloys containing zinc ranging up to 7 percent can be successfully processed with a minimum of fume emission when a cohesive, inert slag cover is used. This nominal figure is subject to some variation depending upon composition of alloy, temperatures, operation procedures, and other factors. Research is still necessary to determine the full range of effects these variables have upon the emission rate.

Copper-base alloys containing 20 to 40 percent zinc have low boiling points of approximately 2,100°F and melting temperatures of approximately 1,700° to 1,900°F. These zinc-rich alloys are poured at approximately 1,900° to 2,000°F, which is only slightly below their boiling points. Pure zinc melts at 787°F and boils at 1,663°F. Even within the pouring range, therefore, fractions of high-zinc alloys usually boil and flash to zinc oxide (Allen et al., 1952). The zinc oxide formed is submicron in size, and its escape to the atmosphere can be prevented only by collecting the fumes and using highly efficient air pollution control equipment.

Characteristics of emissions

Perhaps the best way to understand the difficulty of controlling metallic fumes from brass fur-

Table 80. DUST AND FUME DISCHARGE FROM BRASS FURNACES

Type of furnace	Composition of alloy, %					Type of control	Fuel	Pouring temp, °F	Process wt, lb/hr	Fume emission, lb/hr
	Cu	Zn	Pb	Sn	Other					
Rotary	85	5	5	5	-	None	Oil	No data	1,104	22.5
Rotary	76	14.7	4.7	3.4	0.67 Fe	None	Oil	No data	3,607	25
Rotary	85	5	5	5	-	Slag cover	Oil	No data	1,165	2.73
Elec ind	60	38	2	-	-	None	Elect	No data	1,530	3.47
Elec ind	71	28	-	1	-	None	Elect	No data	1,600	0.77
Elec ind	71	28	-	1	-	None	Elect	No data	1,500	0.54
Cyl reverb	87	4	0	8.4	0.6	None	Oil	No data	273	2.42
Cyl reverb	77	-	18	5	-	None	Oil	2,100	4,267	26.1
Cyl reverb	80	-	13	7	-	Slag cover	Oil	2,100	1,500	22.2
Cyl reverb	80	2	10	8	-	None	Oil	1,900 to 2,100	1,250	10.9
Crucible	65	35	-	-	-	None	Gas	2,100	470	8.67
Crucible	60	37	1.5	0.5	1	None	Gas	1,800	108	0.05
Crucible	77	12	6	3	2	Slag cover	Gas	No data	500	0.822

naces is to consider the physical characteristics of these fumes. The particle sizes of zinc oxide fumes vary from 0.03 to 0.3 micron. Electron photomicrographs of these fumes are shown in Figures 185 and 186. Lead oxide fumes, emitted from many brass alloys, are within this same range of particle sizes. The collection of these very small particles requires high-efficiency control devices. These metallic fumes also produce very opaque effluents, since particles of 0.2- to 0.6-micron diameter produce a maximum scattering of light.

In copper-base alloy foundries, as much as 98 percent of the particulate matter contained in furnace stack gases may be zinc oxide and lead oxide, depending upon the composition of the alloy. A series of tests (Allen et al., 1952) in Los Angeles County indicated the zinc oxide content of fume from representative red and yellow brass furnaces averaged 59 percent, while the lead oxide content averaged 15 percent. Other tests by the same investigators showed that the dust and fume loading from red and yellow brass furnaces varied from 0.022 to 0.771 grain per cubic foot with an average of 0.212 grain per cubic foot at stack conditions.

In high-lead alloys, these tests showed that lead oxide constituted 56 percent of the particulate matter in the exit gas. Lesser constituents of fumes, such as tin, copper, cadmium, silicon, and carbon, may also be present in varying amounts, depending upon the composition of the alloy and upon foundry practice.

Investigations prove conclusively that the most troublesome fumes consist of particles of zinc and lead compounds submicron in size, and that air pollution control equipment capable of collecting particulate matter from 1.0 down to about 0.03 micron is required. Photomicrographs of samples taken when furnace emissions were heavy with smoke resulting from improper combustion or melting of oily scrap indicated that the smoke particles accompanying the fumes may be about 0.01 micron and smaller (Allen et al., 1952).

Factors causing large concentrations of zinc fumes

Four principal factors (Allen et al., 1952) causing relatively large concentrations of zinc fumes in brass furnace gases are:

1. Alloy composition. The rate of loss of zinc is approximately proportional to the zinc percentage in the alloy.

2. Pouring temperature. For a given percentage of zinc, an increase of 100°F increases the rate of loss of zinc about 3 times.

3. Type of furnace. Direct-fired furnaces produce larger fume concentrations than the crucible type does, other conditions being constant. The Los Angeles Nonferrous Foundrymen's Committee, ____ stated, "It is improbable that any open-flame furnace melting alloys containing zinc and lead can be operated without creating excessive emissions. It is conceded that anyone choosing to operate that type of furnace will be required to install control equipment."

4. Poor foundry practice. Excessive emissions result from improper combustion, overheating of the charge, addition of zinc at maxi-

mum furnace temperature, flame impingement upon the metal charged, heating the metal charged, heating the metal too fast, and insufficient flux cover. Excessive superheating of the molten metal is to be avoided for metallurgical and economic as well as pollution control reasons. From an air pollution viewpoint, the early addition of zinc is preferable to gross additions at maximum furnace temperatures.

In any fuel-fired furnace, the internal atmosphere is of prime importance since there exists a constant flow of combustion gases through the melting chamber, more or less in contact with the metal. A reducing atmosphere is undesirable from both the metallurgical and air pollution viewpoints. With too little oxygen, the metal is exposed to a reducing atmosphere of unburned fuel and water vapor, which usually results in gassy metal. Incomplete combustion, especially with

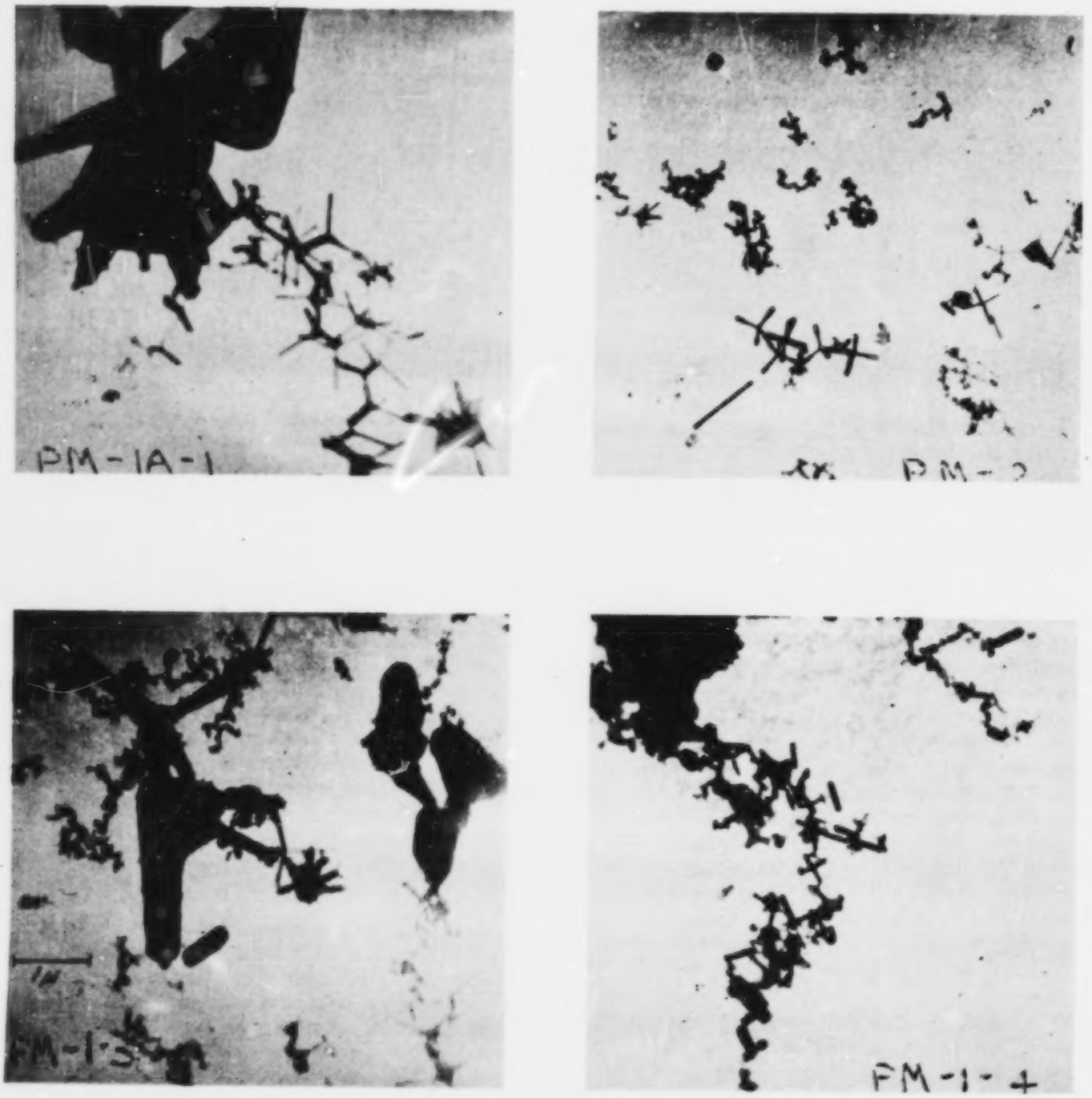


Figure 185. Electron photomicrographs of fume from zinc smelter (Allen et al., 1952).

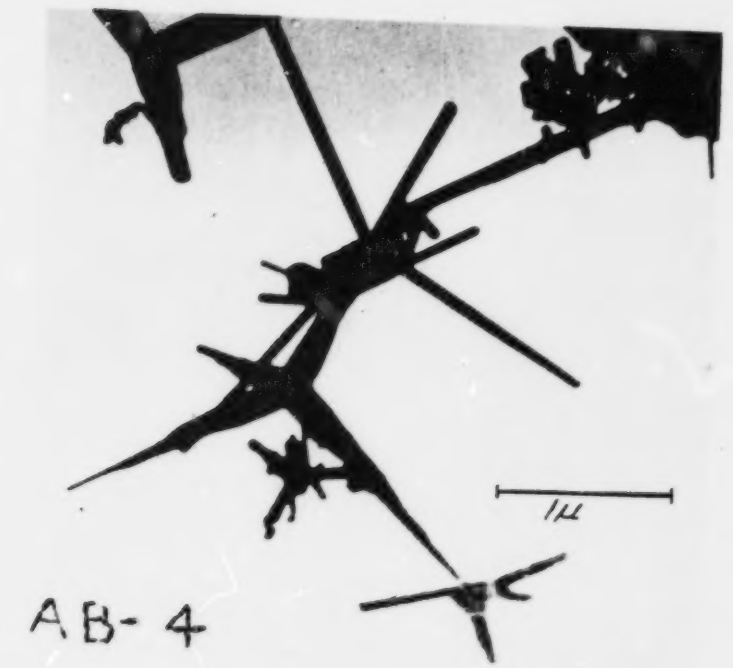


Figure 186. Electron photomicrographs of fume from a yellow brass furnace (Allen et al., 1952).

oil firing, produces smoke and carbon. In one case, a furnace was operated with a fuel mixture so rich that incandescent carbon from the fuel ignited the cloth filter bags in the baghouse serving the furnace. To prevent these difficulties, the atmosphere should be slightly oxidizing. Excess oxygen content should be greater than 0.1 percent; otherwise, castings will be affected by gas porosity. Conversely, the excess oxygen content must be less than 0.5 percent to prevent excessive metal oxidation (St. John, 1955). The need for such close control of the internal furnace atmosphere requires careful regulation of the fuel and air input and frequent checking of the combustion gases.

Crucible furnace--pit and tilt type

The indirect-fired, crucible-type furnace is used extensively in foundries requiring small- and medium-sized melts. The lift-out-type crucible is frequently employed in small furnaces. Tests have demonstrated that, with careful practice and use of slag covers, the crucible furnace is capable of low-fume operation within the legal limits for red brasses containing as much as 7 percent zinc. A slag cover does not sufficiently suppress the emissions from alloys with a zinc content in excess of 7 percent unless very low pouring temperatures are used.

The slag cover, consisting mainly of crushed glass, is not used as a true refining flux but as an inert, cohesive slag of sufficient thickness to keep the molten metal covered. If the quantity of slag is carefully controlled, a minimum of emissions results from either melting or pouring. A slag thickness of 1/4 to 3/8 inch is recommended. Before any metal is added to the crucible, the flux should be added so that, as melting takes place, a cover is formed of sufficient thickness to keep the molten metal divorced from the atmosphere.

When the crucible of molten metal has reached the pouring floor, two holes are punched in the slag cover on top of the metal, one through which the metal is poured, the other to permit the entrance of air (Haley, 1949). Holding escaping oxides to a minimum is possible either by using patented attachments to hold back the slag at the pouring sprue or using a hand-operated skimmer.

Electric furnace--low-frequency induction type

The low-frequency, induction-type furnace has a number of desirable characteristics for melting brasses. The heating is rapid and uniform, and the metal temperature can be accurately controlled. Contamination from combustion gases is completely eliminated. High-frequency induction furnaces are well adapted to copper- and nickel-rich alloys but are not widely used for zinc-rich alloys. Low-frequency induction furnaces are more suitable for melting zinc-rich alloys. During melting of clean metal, use of a suitable flux cover over the metal prevents excessive fuming except during the back charging and pouring phases of the heat. The usual flux covers--borax, soda ash, and others--are destructive to furnace walls, but charcoal is used

with satisfactory results. During the test outlined in Table 81, case C, two-thirds of the total fumes were released during the pouring and charging periods. A furnace, similar to that tested, is shown in Figure 187.

Cupola furnace

The cupola furnace is used for reduction of copper-base alloy slag and residues. The residues charged have a recoverable metallic content of 25 to 30 percent. The balance of the unrecoverable material consists of nonvolatile gangue, mainly, silicates. In addition to the residues, coke and flux are charged to the furnace. Periodically the recovered metal is tapped from the furnace. The slag produced in the cupola is eliminated through a slag tap located slightly above the metal tap.

In addition to the usual metallic fumes, the cupola also discharges smoke and fly ash. Collection of these emissions is required at the cupola stack, the charge door, and the metal tap spout. With no control equipment, emissions of 60 to 100 percent opacity can be expected from the charge door and stack. The opacity of the fumes emitted from the metal tap varies from 60 to 80 percent.

The slag discharged from the cupola is rich in zinc oxide. Although the slag leaves the furnace at a temperature of approximately 1,900°F, the zinc oxide is in solution and, at this temperature, does not volatilize to any extent. The discharge slag is immediately cooled by water. The emissions from the slag-tapping operation rarely exceed 5 percent opacity.

Hooding and Ventilation Requirements

Regardless of the efficiency of the control device, air pollution control is not complete unless all the fumes generated by the furnace are captured. Since different problems are encountered with the various types of furnace, each will be discussed separately.

Reverberatory furnace--open-hearth type

In a reverberatory open-hearth furnace, the products of combustion and metallic fumes are normally vented directly from the furnace through a cooling device to a baghouse. Auxiliary hoods are required over the charge door, rabble (or slag) door, and tap hole. These may vent to the baghouse serving the furnace and hence cool the hot combustion gases by dilution or may vent to a smaller auxiliary baghouse.

Table 81. BRASS-MELTING FURNACE AND BAGHOUSE COLLECTOR DATA

Case	A	B	C
Furnace data			
Type of furnace	Crucible	Crucible	Low-frequency induction
Fuel used	Gas	Gas	Electric
Metal melted	Yellow brass	Red brass	Red brass
Composition of metal melted, %			
Copper	70.6	85.9	82.9
Zinc	24.8	3.8	3.5
Tin	0.5	4.6	4.6
Lead	3.3	4.4	8.4
Other	0.8	1.3	0.6
Melting rate, lb/hr	388	343	1,600
Pouring temperature, °F	2,160	2,350	2,300
Slag cover thickness, in.	1/2	1/2	3/4
Slag cover material	Glass	Glass	Charcoal
Baghouse collector data			
Volume of gases, cfm	9,500	9,700	1,140
Type of baghouse	Sectional tubular	Sectional tubular	Sectional tubular
Filter material	Orlon	Orlon	Orlon
Filter area, ft^2	3,836	3,836	400
Filter velocity, fpm	2.47	2.53	2.85
Inlet fume emission rate, lb/hr	2.55	1.08	2.2[a]
Outlet fume emission rate, lb/hr	0.16	0.04	0.086
Collection efficiency, %	93.7	96.2	96.0

[a]Includes pouring and charging operations.

Figure 187. Low-frequency induction furnace with fixed hood.

Whether the auxiliary hoods vent to the furnace baghouse or to a separate filter, the furnace burners should be turned down or off during periods when the furnace is opened for charging, rabbling, air lancing, removing slag, adding metal, or pouring metal. Otherwise, the exhaust fan may not have sufficient capacity to handle the products of combustion and the additional air required to capture the fumes. Since no two of these operations occur simultaneously, the required air volume for collection may be reduced by the use of properly placed dampers within the exhaust system.

If the entire furnace charge is made at the beginning of the heat, the metal should be loaded in such a way that the flame does not impinge directly upon the charge. If periodic charges are made throughout the heat, the burners should be turned off during charging operations. The opacity of escaping fumes may vary from none to 15 percent with the burners off and may be 60 to 70 percent with the burners ignited.

Well-designed hoods, properly located, with an indraft velocity of 100 to 200 fpm, adequately capture the furnace emissions. If the hood is placed too high for complete capture or is improperly shaped and poorly fitted, higher indraft velocities are required.

The rabble or slag door permits (1) mixing the charge, (2) removing slag from the metal surface, and (3) lancing the metal with compressed air to eliminate iron from the metal when required by alloy specifications. Emissions from the furnace may be of 50 to 90 percent opacity during these operations, even with the burners partially throttled. Again, 100 to 200 fpm indraft velocity is recommended for properly designed hoods.

Generally, after the slag has been removed, metal, usually zinc, must be added to bring the brass within specifications. The furnace metal is at a temperature well above the boiling point of zinc and is no longer covered by the tenacious slag

cover. Hence, voluminous emissions of zinc oxide result. The addition of slab zinc produces 100 percent opaque fumes in great quantity, while a brass addition may generate fumes of 50 percent opacity. A well-designed hood is required over the charge door or rabble door, through which the metal is charged.

Perhaps the most critical operation from the standpoint of air pollution occurs when the furnace is tapped. Nearly continuous emissions of 90 to 100 percent opacity may be expected. Much planning is required to design a hood that completely captures the emissions and yet permits sufficient working room and visibility of the molten metal. Again, the burners should be turned off or throttled as much as possible to reduce the quantity of fumes emitted.

The fluxes used in reverberatory furnaces normally present no air pollution problems. Generally, only nonvolatile fluxes such as borax, soda ash, and iron oxide mill scale are used.

Reverberatory furnace--cylindrical type

Cylindrical-type reverberatory furnaces present all the collection problems of the open-hearth type with the additional complication of furnace rotation. The cylindrical furnace may be rotated up to 90° for charging, slag removing, and metal tapping. With hoods installed in fixed position, the source of emissions may be several feet from the hood, and thus no fumes would be collected. Either a hood attached to the furnace and venting to the control device through flexible ductwork, or an oversized close-fitting hood covering all possible locations of the emission source is required. A close-fitting hood and high indraft velocities are often necessary. For example, an auxiliary hood over the combination charge and slag door of a cylindrical brass furnace was incapable of collecting all emissions, despite an indraft velocity of 1,370 fpm. A similar hood over the pouring spout was also inadequate, despite an indraft velocity of 1,540 fpm. Both hoods were improperly shaped and were located too high above the source for adequate capture.

A cylindrical furnace rotates on its longitudinal axis, and a tight breeching is mandatory at the gas discharge end of the furnace. Adequate indraft velocity must be maintained through the breeching connection to prevent the escape of fumes.

The exhaust system for the cylindrical furnace, as well as for all types of reverberatory furnaces, must be designed to handle the products of combustion at the maximum fuel rate. Any lesser capacity results in a positive pressure within the furnace during periods of maximum firing with resultant emissions from all furnace openings.

Reverberatory furnace--tilting type

The tilting-type furnace differs from the reverberatory furnaces previously discussed in that the exhaust stack is an integral part of the furnace and rotates with the furnace during charging, skimming, and pouring. One type of tilting furnace is charged through the stack, and skimming and pouring are accomplished through a small tap hole in the side of the furnace. Another type has a closeable charge door, and a small port through which the furnace gases escape. These two furnace openings may describe a full 180° of arc during the various phases of a heat.

The wide range of position of the sources makes complete capture of the fumes difficult. One successful system utilizes a canopy hood, with side panels that completely enclose the furnace. Clearance for working around the furnace is provided and a minimum indraft velocity of 125 fpm is required for this opening. This velocity provides complete capture of the emissions unless a cross-draft of 50 to 200 fpm prevails within the furnace room, in which case an estimated 10 percent of the fumes within the furnace hood escape from beneath the hood. This condition is corrected by suspending an asbestos curtain from the windward side of the hood to the floor.

Reverberatory furnace--rotary tilting type

The rotary tilting type of furnace not only tilts for charging and pouring but rotates during the melting period to improve heat transfer. Two types are common. One is charged through the burner end and is poured from the exhaust port of the furnace, opposite the burner. The other has a side charge door at the center of the furnace through which charging, slagging, and pouring operations are conducted.

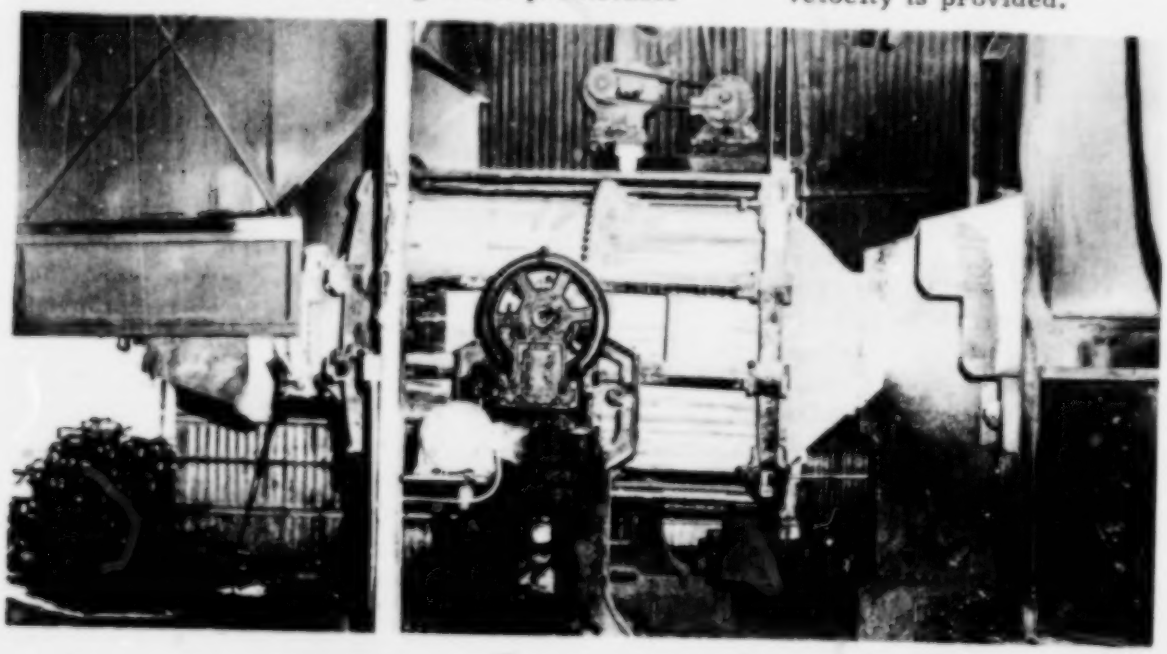
Because of the various movements of this type of furnace, direct connection to the control device is not feasible. The furnace is under positive pressure throughout the heat, and fumes are emitted through all furnace openings.

Hooding a rotary-tilting-type reverberatory furnace for complete capture of fumes is difficult, and complete collection is seldom achieved. These furnaces are undoubtedly the most difficult type of brass furnace to control. To hood them effectively requires a comprehensive design. The major source of emissions occurs at the furnace discharge. Capture of fumes is accomplished by a hood or stack placed approxi-

mately 18 inches from the furnace. This clearance is necessary to allow sufficient room for tilting the furnace for pouring. A minimum indraft velocity of 1,750 fpm is usually required. Although this method controls the emissions during the melting phase, capturing the dense fumes generated during the pour is difficult.

Hooding is sometimes installed at the burner end of a furnace to capture emissions that may escape from openings during melting, or particularly during the time the furnace is tilted to pour. Because both ends of the furnace are open, a venting action is created during the pour, causing fume emissions to be discharged from the elevated end of the furnace. Close hooding is not practicable because the operator must observe the conditions within the furnace through the open ends. An overhead canopy hood is usually installed. Figure 188 illustrates an installation in which a canopy hood is used to capture emissions from one end of the furnace while, at the opposite end, baffles have been extended from around the stack opening to minimize crossdrafts and aid in capturing emissions from the ladle being filled from the furnace.

Additional heavy emissions may be expected during charging, alloying, and slagging. High-overhead canopy hoods are generally used. These overhead hoods are, however, unsatisfactory unless they cover a large area, and a high indraft velocity is provided.



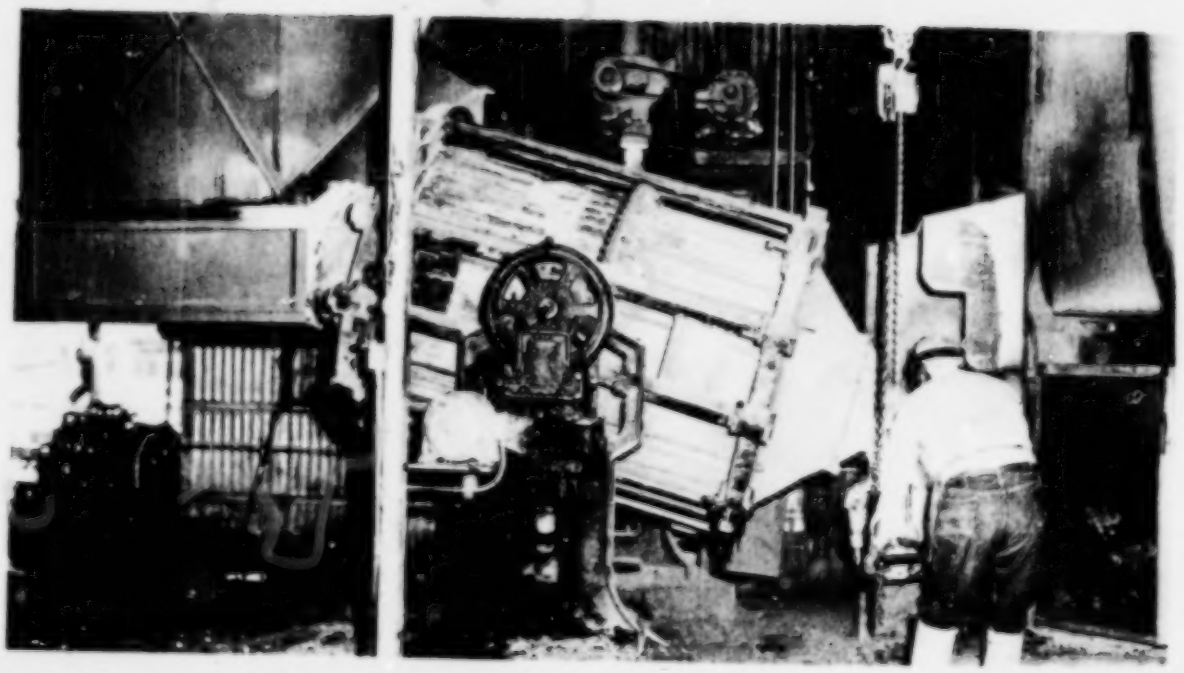


Figure 188. Rotary-tilting-type reverberatory furnace venting to canopy hood and stack vent: (top) Furnace during meltdown, (bottom) furnace during pour (Valley Brass, Inc. El Monte, Calif.).

The need for numerous hoods and large air volumes, with the resultant larger control device, makes the tilting-type open-flame furnace expensive to control. This type of furnace is being gradually replaced by more easily controllable equipment.

The following example illustrates the fundamental design considerations of a side-draft hood for a rotary-tilting-type furnace.

Example 28

Given:

Rotary-tilting-type brass-melting furnace. Fuel input, 17 gal/hr U.S. Grade No. 5 fuel oil. Maximum temperature of products of combustion discharged from furnace, 2,600°F.

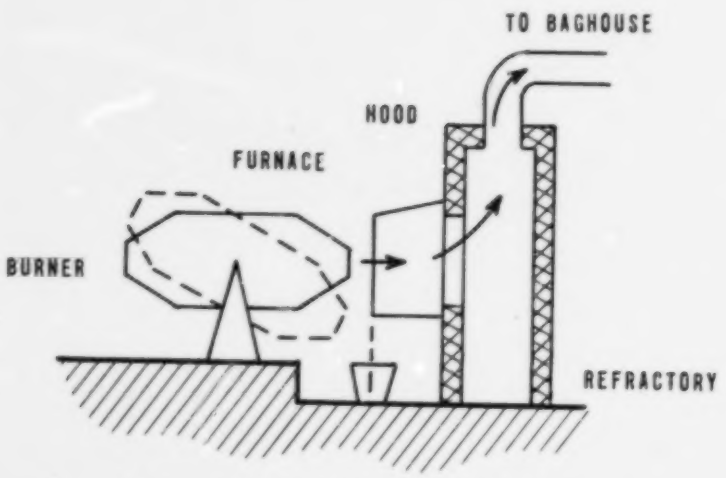


Figure 189. Rotary-tilting-type brass-melting furnace.

Problem:

Determine the design features of a side-draft hood to vent the furnace.

Solution:

1. Volume and weight of products to be vented from furnace:

With 10% excess air, 1 lb of U.S. Grade No. 5 fuel oil yields 206.6 ft^3 or 15.96 lb of products of combustion. One gallon of fuel oil weighs 8 lb.

$$\text{Vol} = \frac{(17)(8)(206.6)}{60} = 468 \text{ scfm}$$

$$\text{Wt} = \frac{(17)(8)(15.96)}{60} = 36.2 \text{ lb/min}$$

2. Volume of ambient air required to reduce temperature of products of combustion from 2,600° to 250°F:

Baghouse inlet design temperature selected, 250°F. Ambient air temperature assumed to be 100°F.

$$\left.\begin{matrix}\text{Heat gained by} \\ \text{ambient air}\end{matrix}\right\} = \left\{\begin{matrix}\text{Heat lost by products} \\ \text{of combustion}\end{matrix}\right.$$

$$M_a C_p \Delta t_a = M_{pc} C_p \Delta t_{pc}$$

$$(M_a)(0.25)(250-100) = (36.2)(0.27)(2,600-250)$$

$$37.5\, M_a = 23,000$$

$$M_a = 613 \text{ lb/min}$$

$$\text{or} \quad \frac{613}{0.071} = 8,640 \text{ cfm at } 100°F$$

3. Total volume of products to be vented through hood:

$$\text{Volume from furnace} = (468)\left(\frac{250 + 460}{60 + 460}\right)$$

$$= 639 \text{ cfm}$$

$$\text{Volume from ambient air} = (8,640)\left(\frac{250 + 460}{100 + 460}\right)$$

$$= 10,950 \text{ cfm}$$

$$\text{Total} = 11,589 \text{ cfm at } 250°F$$

4. Open area of hood: Design for a velocity of 2,000 ft/min. This is adequate to ensure good pickup if the hood geometry is designed properly.

$$\frac{11,589}{2,000} = 5.78 \text{ ft}^2$$

Problem note: Furnace gases should discharge directly into center of hood opening. Positioning of the hood should be such that it picks up emissions from the ladle during the furnace tilt and pour. Sides extending to ground level may be necessary to nullify crossdrafts. When the

furnace is tilted, emissions will escape from the high side or the firing end opening. These may be stopped by blowing a portion of the burner combustion air through the furnace, which forces emissions through the furnace discharge opening. If this is not possible, an auxiliary hood should be installed over the firing end of the furnace.

Crucible-type furnaces

One large-volume foundry, using tilting-type crucible furnaces, installed an exhaust system to control emissions during pouring. The exhaust system vents 14 furnaces to a baghouse. The hooding collects all the fumes during pouring without interfering with the furnace operation in any way. The hood is equipped with a damper that is closed when the furnace is in the normal firing position. A linkage system opens the damper when pouring begins. After the furnace is tilted 40°, the damper is fully opened, remaining there for the rest of the pour. It swings shut automatically when the furnace is returned to the firing position. The ductwork leading from the hood pivots when the furnace is tilted. The entire hood is fixed to the furnace with two bolts, which permit its rapid removal for periodic repairs to the furnace lining and crucible. Since only one furnace is poured at a time and the system operates only during the pour, only 1,500 cfm is required to collect the fumes. Tests show that the amount of particulate matter emitted to the atmosphere with this system is 0.125 pound per hour per furnace (Anonymous, 1950). This contrasts with a loss of over 2 pounds per hour uncontrolled.

Figure 190 shows an installation of a tilting-type brass crucible furnace with a plenum roof-type hood, which captures furnace emissions during the meltdown and ladle emissions during the pour.

Emissions resulting from the pouring of molten metal from a ladle into molds can also be controlled by two other devices. The first is a fixed pouring station that is hooded so that emissions from the ladle and molds are captured during the pouring (Figure 191). An installation of this type requires a conveyorized mold line. The second is a small hood attached to the pouring ladle and vented to the control system through flexible ductwork connections. Within the limits of the flexible connection, the hood can travel with the ladle from mold to mold as each is poured (Figure 192).

Low-frequency induction furnace

The control of the emissions from an induction furnace is much more expensive and difficult if oily turnings are charged to the furnace. In addition to the fumes common to brass melting, great clouds of No. 5 Ringelmann black smoke are generated when the oily shavings contact the molten heel within the furnace. Adequate hooding enclosing the furnace is, therefore, required, and a large volume of air is necessary to capture the smoke and fumes. Where 900 cfm was suffi-

Figure 190. Tilt-type crucible brass furnace with a plenum roof-type hood.

Figure 191. Fixed-mold pouring station with fume mold.

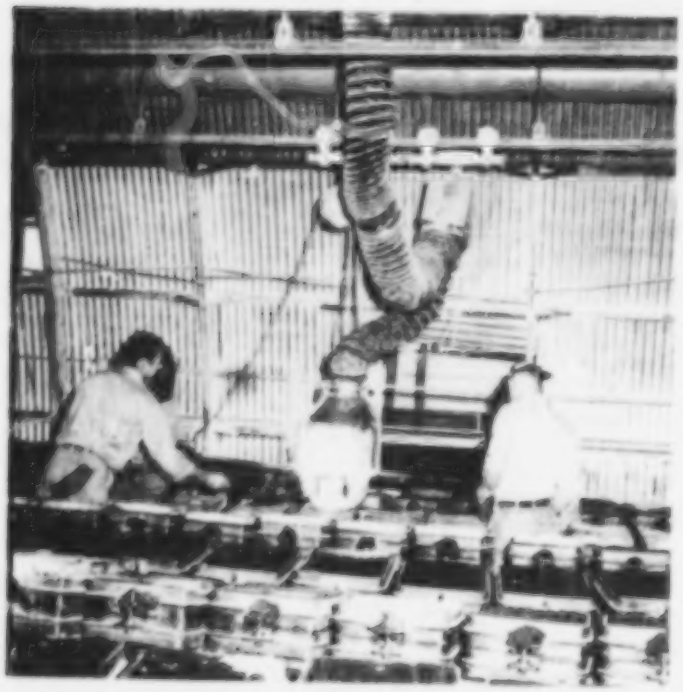


Figure 192. Pouring ladle with traveling fume hood (Valley Brass, Inc., El Monte, Calif.).

cient to collect the pouring emissions from an induction furnace using oil-free metal, 10,000 cfm was required throughout the heat for a similarly sized furnace melting turnings with a 3 percent oil content. Figure 193 shows an induction furnace with an adjustable low-canopy hood that can be positioned to cover both meltdown and pouring operations. A baghouse collects the fume.

Another, smaller induction furnace is shown in Figure 194. In addition to capturing furnace emissions during meltdown, the hood captures emissions during the pour into the ladle. Figure 195 shows the extent of emissions after the ladle is removed from the hood area.

Cupola furnace

An exhaust system to control a cupola must have sufficient capacity to remove the products of combustion, collect the emissions from the metal tap spout, and provide a minimum indraft velocity of 250 fpm through the charge door. In addition, side curtains may be required around the charge door to shield adverse crosscurrents. A canopy hood is recommended for the metal tap spout. The air requirement for this hood is a function of its size and proximity to the source of emissions.

Air Pollution Control Equipment

Baghouses

Baghouses with tubular filters are used to control the emissions from brass furnaces. This type of collector is available in many useful and effective forms. Wool, cotton, and synthetic filter media effectively separate submicron-sized particulate matter from gases because of the filtering action of the "mat" of particles previously collected.

The gases leaving a reverberatory furnace may be 100° to 200°F hotter than the molten metal and must be cooled before reaching the filter cloth. Direct cooling, by spraying water into the hot combustion gases, is not generally practiced because (1) there is increased corrosion of the ductwork and collection equipment, (2) the vaporized water increases the exhaust gas volume, necessitating a correspondingly larger baghouse, and (3) the temperature of the gases in the baghouse must be kept above the dewpoint to prevent condensation of water on the bags. The exhaust gases may be cooled by dilution with cold air, but this increases the size of the control equipment and the operating costs of the exhaust system.

One cooling system employed consists of a water-jacketed cooler followed by air-cooled radiation-convection columns, as shown in Figure 195. The water-jacketed section reduces the temperature from approximately 2,000° to 900°F. The radiation-convection coolers then reduce the temperature to the degree required to protect the fabric of the filter medium. Figure 196 depicts an actual installation showing the cooling columns and baghouse.

Treated orlon is gradually replacing glass cloth as the most favored high-temperature fabric. Although glass bags withstand higher temperatures, the periodic shaking of the bags gradually breaks the glass fibers and causes higher maintenance costs.

Probably the most critical design factor for a tubular baghouse is the filtering velocity. A filtering velocity of 2.5 fpm is recommended for collecting the fumes from brass furnaces with relatively small concentrations of fume. Larger concentrations of fume require a lower filtering velocity. A higher filtering velocity requires more frequent shaking to maintain a pressure drop through the baghouse within reasonable limits. Excessive bag wear results from frequent shaking and higher filtering velocities. A pressure drop of 2 to 5 inches of water column is normal, and high pressure differentials across the bags are to be avoided.

The baghouse should be completely enclosed to protect the bags from inclement weather and water condensation during the night when the equipment is usually idle. The exhaust fan should be placed downstream from the baghouse to prevent blade abrasion. Moreover, problems with fan balance due to material's adhering to the

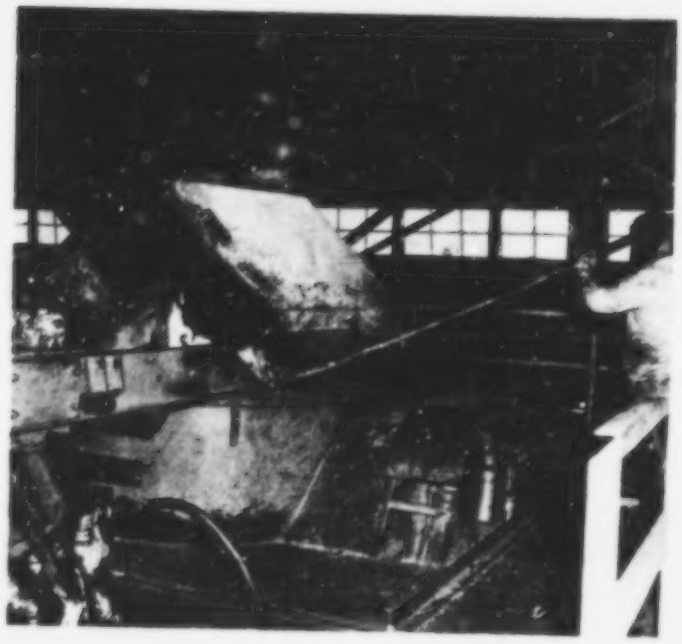


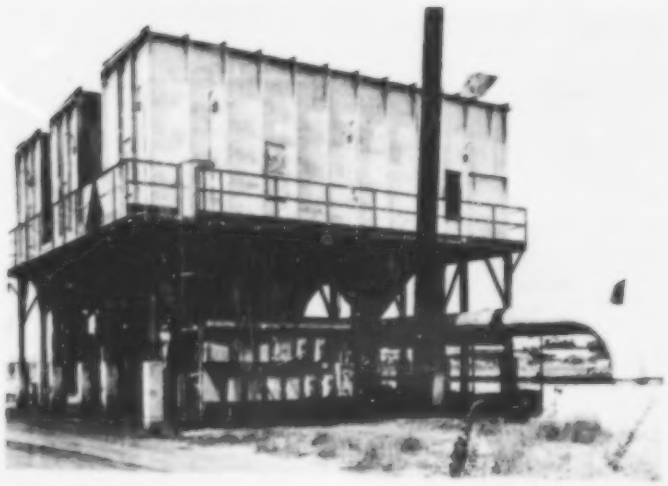
Figure 193. Electric induction tilting-type brass furnace with adjustable canopy hood and baghouse control device (American Brass Company, Paramount, Calif.).

Furnace data

Type, electric induction	Electrical rating, 450 kw
Capacity, 3,000 lb/hr	Metal processed, brass

Control system data

Fan motor rating, 30 hp	Filtering velocity, 1.6 fpm
Gas volume, 12,700 cfm	Pressure drop, 1.8 to 4 in. WC
Baghouse type, compartmented, tubular	Gas stream cooling, temperature-controlled water sprays in duct
Filter area, 7,896 ft^2	Hood indraft velocity, 560 ft/min
Filter medium, orlon	
Shaking, automatic by compartment	



blades will not occur. Furthermore, broken bags are more easily detected when the exhaust system discharges to the atmosphere through one opening.

In Table 81, the results of tests performed on baghouses venting brass furnaces are shown. Note that the melting rate of the induction furnace is over 4 times that of the crucible gas-fired furnaces, yet the baghouse is only one-tenth as large. Larger baghouses are necessary for crucible gas-fired furnaces because of the heat and volume of the products of combustion from the gas burners.

Electrical precipitators

Generally, electrical precipitators are extremely effective collectors for many substances in any size range from 200 mesh (74 μ) to perhaps 0.001 micron, wet or dry, ambient or up to 1,200 F. This equipment has not, however, proved entirely satisfactory on lead and zinc fumes. Lead oxide in particular is difficult to collect because of its relatively high resistivity, which can cause a high potential to develop across the dust layer on the collecting surface. This not only reduces the potential across the gas stream but may result in spark discharge with resultant back ionization and reentrainment of dust. In addition, high-voltage precipitators have not been available in small units suitable for small nonferrous foundry use, and the first cost may, moreover, be prohibitive.

Scrubbers

Dynamic scrubbers or mechanical washers have proved in some applications to be effective from

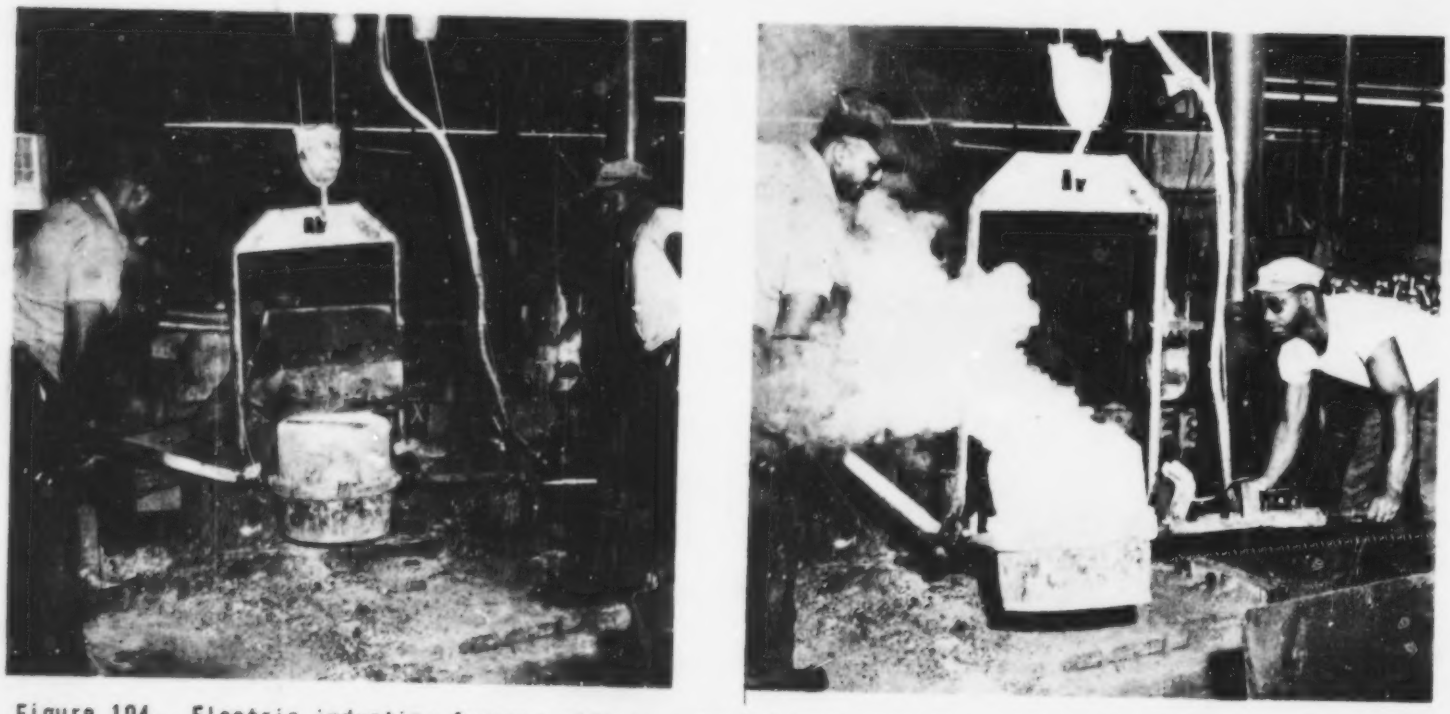


Figure 194. Electric induction furnace with an extended hood over the pouring area: (left) Hood in place during pouring operations, (right) ladle removed from the hood area (Western Brass Works, Los Angeles, Calif.).

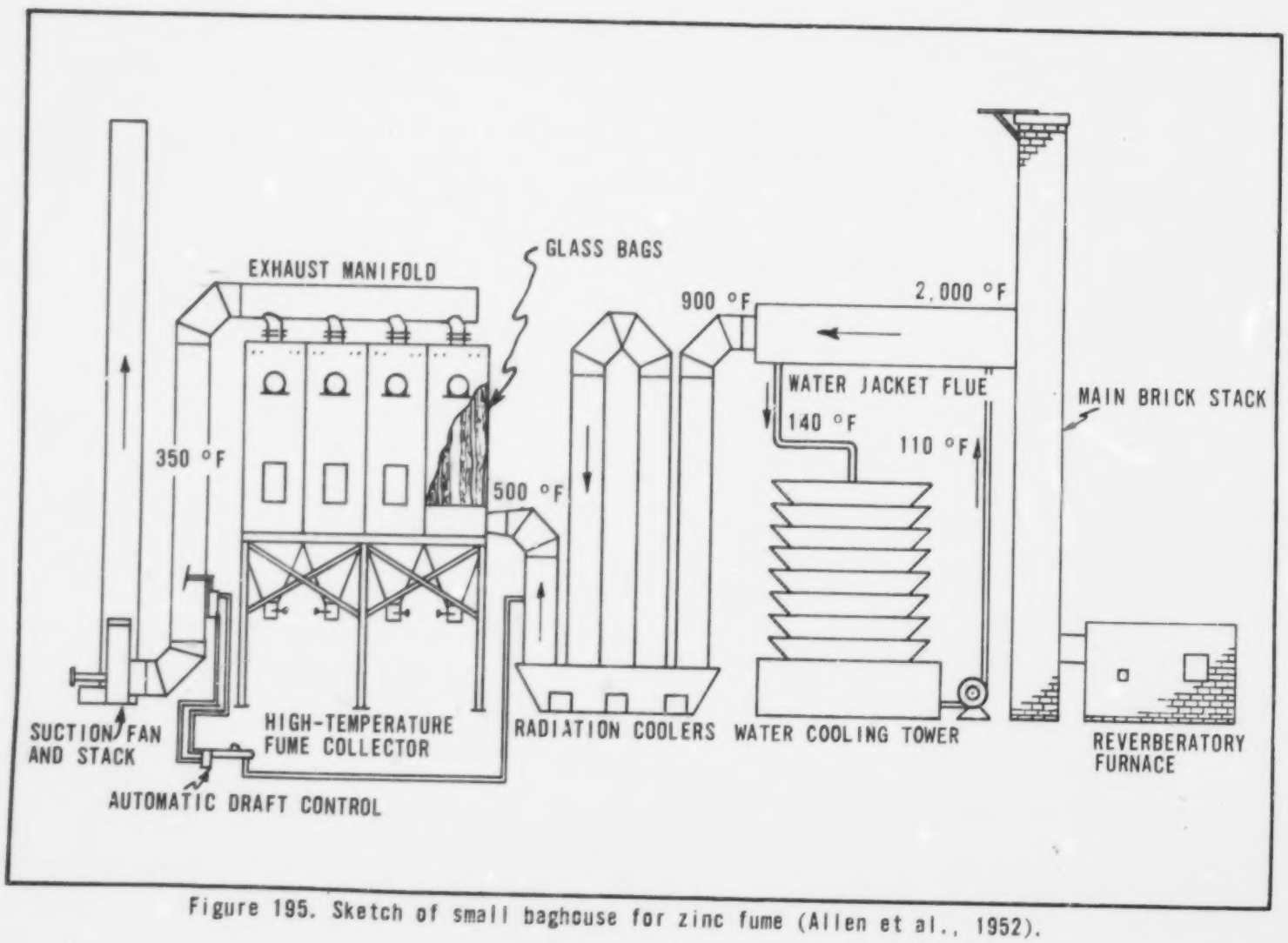


Figure 195. Sketch of small baghouse for zinc fume (Allen et al., 1952).

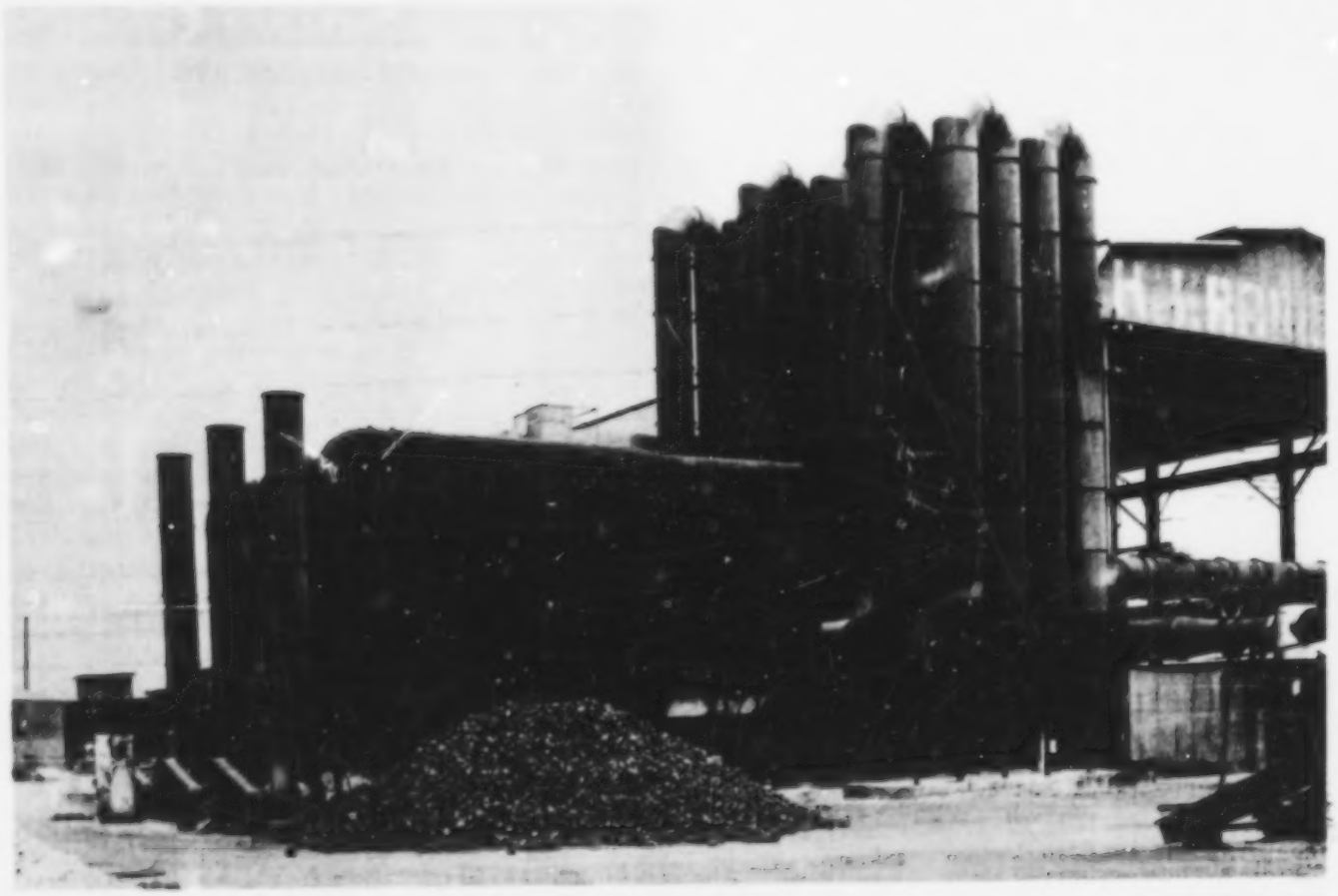


Figure 196. Reverberatory open-hearth furnace whose slagging door and tap hole hoods vent to radiation convection cooling columns and baghouse (H. Kramer and Company, El Segundo, Calif.).

Furnace data

Type, reverberatory
Capacity, 50 ton
Fuel input, 7,260,000 Btu/hr
Temperature of gas discharge, 2,300°F

Control system data

Three baghouses in parallel serve three reverberatory furnaces and other smaller furnaces.
Fan motor rating, three 50 hp
Maximum gas volume, 54,400 cfm
Baghouse inlet temperature, 220°to 250°F
Filter medium, orlon
Baghouse type, compartmented, tubular
Filter area (3 houses), 27,216 ft^2
Maximum filter ratio, 2:1
Shaking, automatic by compartment

10 to 1 micron, but in addition to being ineffective in the submicron range, they have the disadvantage of high power consumption and mechanical wear and usually require separation of the metallic fumes and other particulate matter from the circulating water.

A number of dynamic and static scrubbers have been tested on brass furnaces and all have been found unsatisfactory. The scrubbers not only failed to reduce the particulate matter sufficiently, but the opacity of the fumes escaping collection was excessive. The results of several scrubber tests are summarized in Table 82. These scrubbers have been replaced by baghouses.

Collectors depending upon centrifugal principles alone are not adapted to brass furnace dust collection because of the low efficiency of these devices on submicron-sized particulate matter. One Los Angeles foundry operated a wet cyclone gas conditioner venting to a wet entrainment separator for recovering partially agglomerated zinc oxide fume. The concentration of particulate matter was relatively small, since tilting crucible furnaces with slag covers were used, and the device was able to reduce the weight of the dust and fumes emitted below the legal limits, but the number of unagglomerated submicron-sized particles escaping collection was sufficient to cause periodic opacity violations. Consequently, this unit has been replaced by a baghouse.

Table 82. EFFICIENCIES OF WET SCRUBBER CONTROL DEVICES SERVING BRASS-MELTING FURNACES

Type of scrubber	Water rate, gpm	Flue gas volume, scfm	Particulate matter, gr/scf		Total dust, lb/hr		Efficiency, %
			In	Out	In	Out	
Venturi with wet cyclone	7.6	860	2.71	0.704	19.95	7.04	65
Dynamic wet	20.0	770	0.905	0.367	5.97	3.00	50
Dynamic wet	50.0	1,870	1.76	0.598	28.2	13.2	53

SECONDARY ALUMINUM-MELTING PROCESSES

TYPES OF PROCESS

Secondary aluminum melting is essentially the process of remelting aluminum, but the term encompasses the following additional practices:

1. Fluxing. This term is applied to any process in which materials are added to the melt to aid in removal of gases, oxides, or other impurities, but do not remain in the final product.

2. Alloying. This term is applied to any process in which materials are added to give desired properties to the product and become part of the final product.

3. Degassing. This includes any process used to reduce or eliminate dissolved gases.

4. "Demagging." This includes any process used to reduce the magnesium content of the alloy.

These terms are often used vaguely and overlap to a great extent. For example, degassing and demagging are usually accomplished by means of fluxes. The use of zinc chloride and zinc fluoride fluxes increases the zinc content of aluminum alloys.

Aluminum for secondary melting comes from three main sources:

1. Aluminum pigs. These may be primary metal but may also be secondary aluminum produced by a large secondary smelter to meet standard alloy specifications.

2. Foundry returns. These include gates, risers, runners, sprues, and rejected castings. In foundries producing sand mold castings, foundry returns may amount to 40 to 60 percent of the metal poured.

3. Scrap. This category includes aluminum contaminated with oil, grease, paint, rubber, plastics,and other metals such as iron, magnesium, zinc, and brass.

The melting of clean aluminum pigs and foundry returns without the use of fluxes does not result in the discharge of significant quantities of air contaminants. The melting of aluminum scrap, however, frequently requires air pollution control equipment to prevent the discharge of excessive air contaminants.

Crucible Furnaces

For melting small quantities of aluminum, up to 1,000 pounds, crucible or pot-type furnaces are used extensively. Almost all crucibles are made of silicon carbide or similar refractory material. Small crucibles are lifted out of the furnace and used as ladles to pour into molds. The larger crucibles are usually used with tilting-type furnaces. For die casting, molten metal is ladled out with a small hand ladle or it can be fed automatically to the die-casting machine.

Reverberatory Furnaces

The reverberatory furnace is commonly used for medium- and large-capacity heats. Small reverberatory furnaces up to approximately 3,000 pounds' capacity may be of the tilting type. Sometimes a double-hearth construction is employed in furnaces of 1,000 to 3,000 pounds' holding

capacity. This permits melting to take place in one hearth, the second hearth serving only to hold the molten metal at the appropriate temperature. Advocates of this design stress that it reduces or eliminates the tendency of the metal to absorb gas. The contention is that porosity results from hydrogen gas, which is liberated from moisture trapped below the surface of molten aluminum. The use of a double hearth permits moisture to be driven off before the metal melts and runs to the holding hearth. Sometimes the melting hearth is also used as a sweat furnace to separate the aluminum from contaminants such as brass and steel. The use of double-hearth furnaces for the larger capacity heats is not common.

A charging well is frequently used on aluminum reverberatory furnaces. Figure 197 shows a 20-ton reverberatory furnace with a charging well. The well permits chips and other small aluminum scrap to be introduced and immersed below the liquid level. Chips and small scrap have an unusually high surface area-to-volume relationship, and oxidation must be minimized. Large quantities of flux are also added and stirred in to dissolve the oxide coating and aid in the removal of dirt and other impurities. The flux causes the oxides and other impurities to rise to the surface in the form of a dross that can be skimmed off easily.

Reverberatory furnaces of 20- to 50-ton holding capacity are common. Usually one heat is produced in a 24-hour period; however, the time per heat in different shops varies from 4 hours to as much as 72 hours. This type of furnace is commonly used to melt a variety of scrap. The materials charged, method of charging, size and design of the furnace, heat input, and fluxing, refining, and alloying procedures all have some influence on the time required to complete a heat. After the charge is completely melted, alloying ingredients are added to adjust the composition to required specifications. Large quantities of fluxes are added when scrap of small size and low grade is melted. The flux in some cases may amount to as much as 30 percent of the weight of scrap charged.

Fuel-Fired Furnaces

Both gas- and oil-fired furnaces are common, though gas-fired furnaces are usually preferred. Frequently, combination burners are used so that gas may be burned when available, with oil substituted during periods of gas curtailment.

Fuel-fired furnaces used for aluminum melting are extremely inefficient. Approximately 50 percent of the gross heating value in the fuel is unavailable in the products of combustion. Radiation and convection losses are high since little or no insulation is used. Many small crucible furnaces probably do not achieve more than 5 percent overall efficiency and some may not exceed 2 to 3 percent (Anderson, 1925). At the other extreme a properly designed and operated furnace may be able to use as much as 20 percent of the gross heat in the fuel. Most furnaces can be assumed to operate with efficiencies of 5 to 15 percent. This may become an important factor when air pollution control equipment must be provided to handle the products of combustion. Fortunately, this is seldom necessary. Controls, if provided, are usually required only during the degassing or demagging operations when the burners are off. Another possibility is to add fluxes and scrap only to a charging well that is vented to control equipment.

Electrically Heated Furnaces

Electric induction furnaces are becoming increasingly common for both melting and holding aluminum in spite of higher installation and operating costs. Some of the advantages they offer over other furnaces are higher efficiency, closer temperature control, no contaminants from products of combustion, less oxidation, and improved homogeneity of metal. Electric resistance heating is sometimes used for holding but rarely for melting furnaces. Most electric furnaces for aluminum melting are relatively small though some holding furnaces have capacities up to about 15 tons.

Charging Practices

Small crucible furnaces are usually charged by hand with pigs and foundry returns. Many reverberatory furnaces are also charged with the same type of materials, but mechanical means are used because of the larger quantity of materials involved.

When chips and light scrap are melted, it is a common practice to melt some heavier scrap or pigs first to form a molten "heel." The light scrap is then added and immediately immersed below the surface of the molten metal so that further oxidation is prevented. The heel may consist of 5,000 to 20,000 pounds, depending upon the size of the furnace.

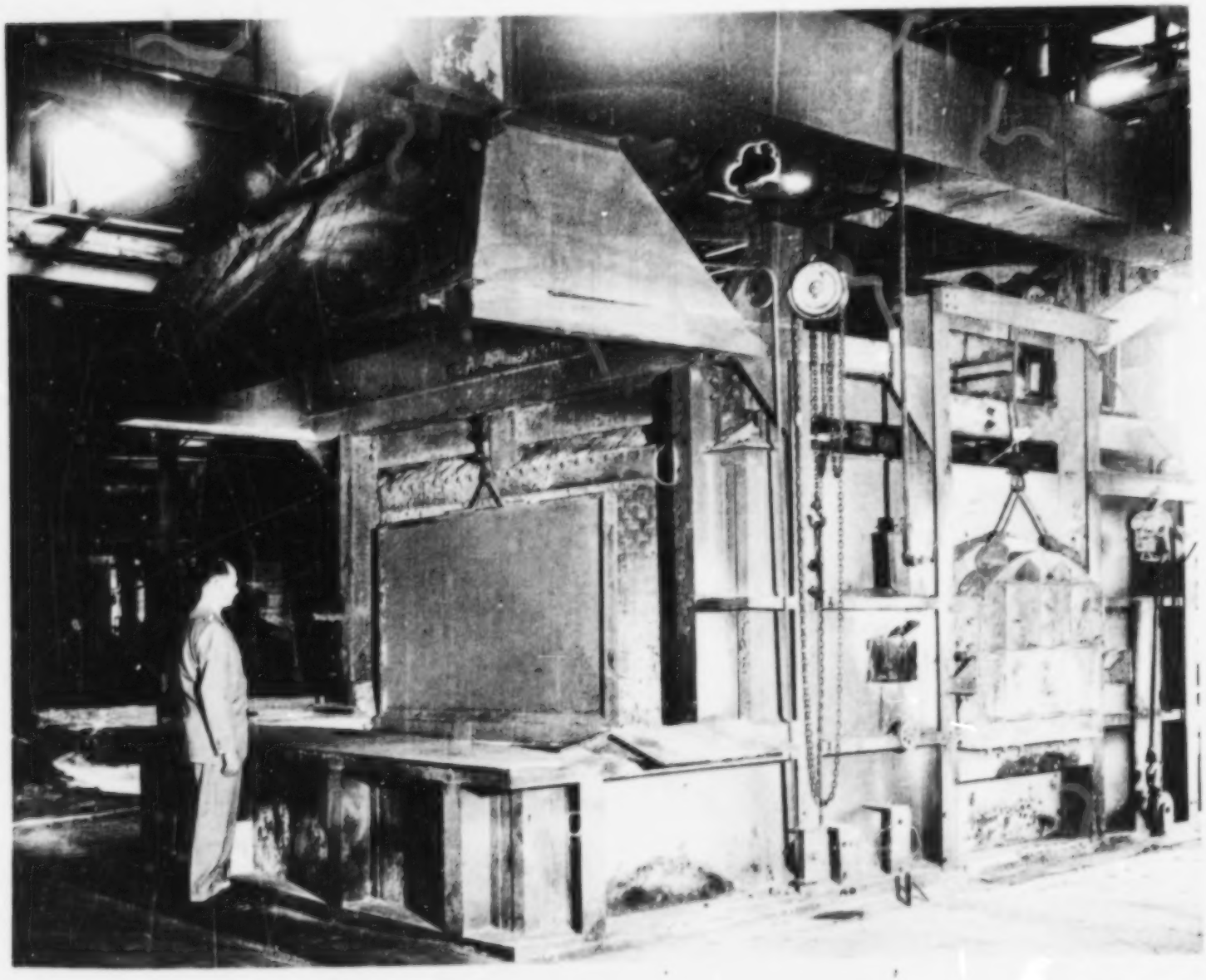


Figure 197. A 20-ton aluminum-melting reverbatory furnace with charging well hood (Aaron Ferrer & Sons Inc., Los Angeles, Calif.).

Pouring Practices

Tilting-type crucible furnaces are used when the crucible is too large to be handled easily. These furnaces are poured into smaller capacity ladles for transfer to the molds. Larger reverberatory furnaces are either tapped from a tap hole or siphoned into a ladle. Ladles vary up to 3 or 4 tons capacity in some cases. Sometimes the ladles are equipped with covers with electric resistance heaters to prevent loss of temperature when the ladle is not to be poured immediately or when the pouring requires too long a time. Pouring molten aluminum does not usually result in the discharge of air contaminants in significant quantities.

Fluxing

The objectives of fluxing generally fall into four main categories:

1. Cover fluxes. These fluxes are used to cover the surface of the metal to prevent further oxidation and are usually liquid at the melting point of aluminum. Some of these are also effective in preventing gas absorption.

2. Solvent fluxes. These fluxes generally cause the impurities and oxides to float on top of the melt in the form of a dross that can be skimmed off easily.

3. Degassing fluxes. These fluxes are used to purge the melt of dissolved gases. The dissolved gas is assumed to be hydrogen, but other gases are also highly soluble in aluminum. The solubility of gases in molten aluminum increases with temperature. The gases most soluble in molten aluminum, in decreasing order of solubility, are hydrogen, methane, carbon dioxide, sulfur dioxide, oxygen, air, and carbon monoxide. The solubility of hydrogen is 6 or 7 times as great as that of methane and over 10 times that of carbon dioxide. Elimination of hydrogen gas in aluminum is a major problem.

4. Magnesium-reducing fluxes. These fluxes are used to reduce the magnesium content of the alloy (known as demagging). During World War II it became necessary to recover large quantities of aluminum scrap, much of which had a magnesium content too high for the intended use. It was found that the magnesium could be selectively removed by the use of appropriate fluxes.

The quantity and type of fluxing depend upon the the type of furnace, the materials being melted, and the specifications of the final product. A few operators melting only pigs and returns find fluxing unnecessary. At the other extreme are large secondary smelters that process very low-grade scrap and sometimes use fluxes amounting to as much as one-third of the weight of the aluminum scrap charged. About 10 percent by weight is an average figure for the amount of flux used for medium- to low-grade scrap.

Fluxes for degassing or demagging may be either solids or gases. The gaseous types are usually preferred because they are easier to use, and the rate of application is simpler to control. Some of these, for example chlorine, may be used for either degassing or demagging, depending upon the metal temperature. In general, any flux that is effective in removing magnesium also removes gas inclusions.

Cover fluxes

Cover fluxes are used to protect the metal from contact with air and thereby prevent oxidation. Most of these fluxes use sodium chloride as one of the ingredients (Anderson, 1931). Various proportions of sodium chloride are frequently used with calcium chloride and calcium fluoride. Sometimes cryolite or cryolite with aluminum fluoride is added to dissolve oxides. Borax has also been used alone and in combination with sodium chloride.

Solvent fluxes

Solvent fluxes usually form a gas or vapor at the temperature of the melt. Their action is largely physical. The resulting agitation causes the oxides and dirt to rise to the top of the molten metal where they can be skimmed off. Included in this group are aluminum chloride, ammonium chloride, and zinc chloride. Zinc chloride increases the zinc content of the alloy probably according to the equation

$$3\,ZnCl_2 + 2\,Al \rightarrow 3\,Zn + 2\,AlCl_3 \quad (100)$$

Aluminum chloride, which is formed in this reaction, is a vapor at temperatures above 352°F. It bubbles out of the melt, forming a dense white fume as it condenses in the atmosphere.

So-called chemical fluxes are solvents for aluminum oxide. Cryolite, other fluorides, or borax is used for this purpose. Part of the action of the fluorides is thought to be due to the liberation of fluorine, which attacks silicates and dirt. Some chlorides are also used extensively, but their action is not understood.

Degassing fluxes

There are many methods of removing dissolved gas from molten aluminum, some of which do not require the addition of a flux. Among the nonflux methods are the use of vibration, high vacuum, and solidification with remelting. None is as effective as the use of an active agent such as chlorine gas. Helium, argon, and nitrogen gases have also been used successfully. Solid materials that have been used include many metallic chlorides. Some think that their action is physical rather than chemical and that one gas is as good as another. For this reason, nitrogen has been used extensively. Nitrogen is not toxic, and virtually no visible air contaminants are released when it is used. In addition, it does not coarsen the grain or remove sodium or magnesium from the melt. The main objection to the use of nitrogen is that commercial nitrogen is usually contaminated with oxygen and water vapor (Eastwood, 1946).

Magnesium-reducing fluxes

The use of fluxes to reduce the magnesium content of aluminum alloys is a relatively new procedure. Certain fluxes have long been known to tend to reduce the percent of magnesium in the alloy, but this process did not become commonplace until the advent of World War II. Several fluxes may be used for this purpose. Aluminum

fluoride and chlorine gas are perhaps the most commonly used. The temperature of the melt must be significantly greater in demagging than in degassing, usually between 1,400° and 1,500°F.

As much as 1 ton of aluminum fluoride is commonly used in reverberatory furnaces of 40- to 50-ton capacity. The aluminum fluoride is usually added to the molten metal with smaller quantities of other fluxes such as sodium chloride, potassium chloride, and cryolite, and the entire melt is stirred vigorously. Magnesium fluoride is formed, which can then be skimmed off. Large quantities of air contaminants are discharged from this process.

Chlorine gas for this purpose is easier to regulate, but extra precautions must be taken because of the extreme toxicity of this material. The chlorine is fed under pressure through the tubes or lances to the bottom of the melt and permitted to bubble up through the molten aluminum. Figure 198 (left) shows a ladle of aluminum before the lances are lowered into the metal. Figure 198 (right) shows the hood in position.

THE AIR POLLUTION PROBLEM

Frequently, a large part of the material charged to a reverberatory furnace is low-grade scrap and chips. Paint, dirt, oil, grease, and other contaminants from this scrap cause large quantities of smoke and fumes to be discharged. Even if the scrap is clean, large surface-to-volume ratios require the use of more fluxes, which can cause serious air pollution problems.

In a study of the extent of visible emissions discharged from degassing aluminum with chlorine gas, the major parameters were found to be metal temperature, chlorine flow rate, and magnesium content of the alloy. Other factors affecting the emissions to a lesser degree are the depth at which the chlorine is released and the thickness and composition of the dross on the metal surface. Other factors remaining constant, the opacity of the emissions at any time is an inverse function of the percent magnesium in the metal at that time.

When the magnesium content is reduced, either by combining with chlorine to form magnesium chloride ($MgCl_2$) or by using an alloy containing

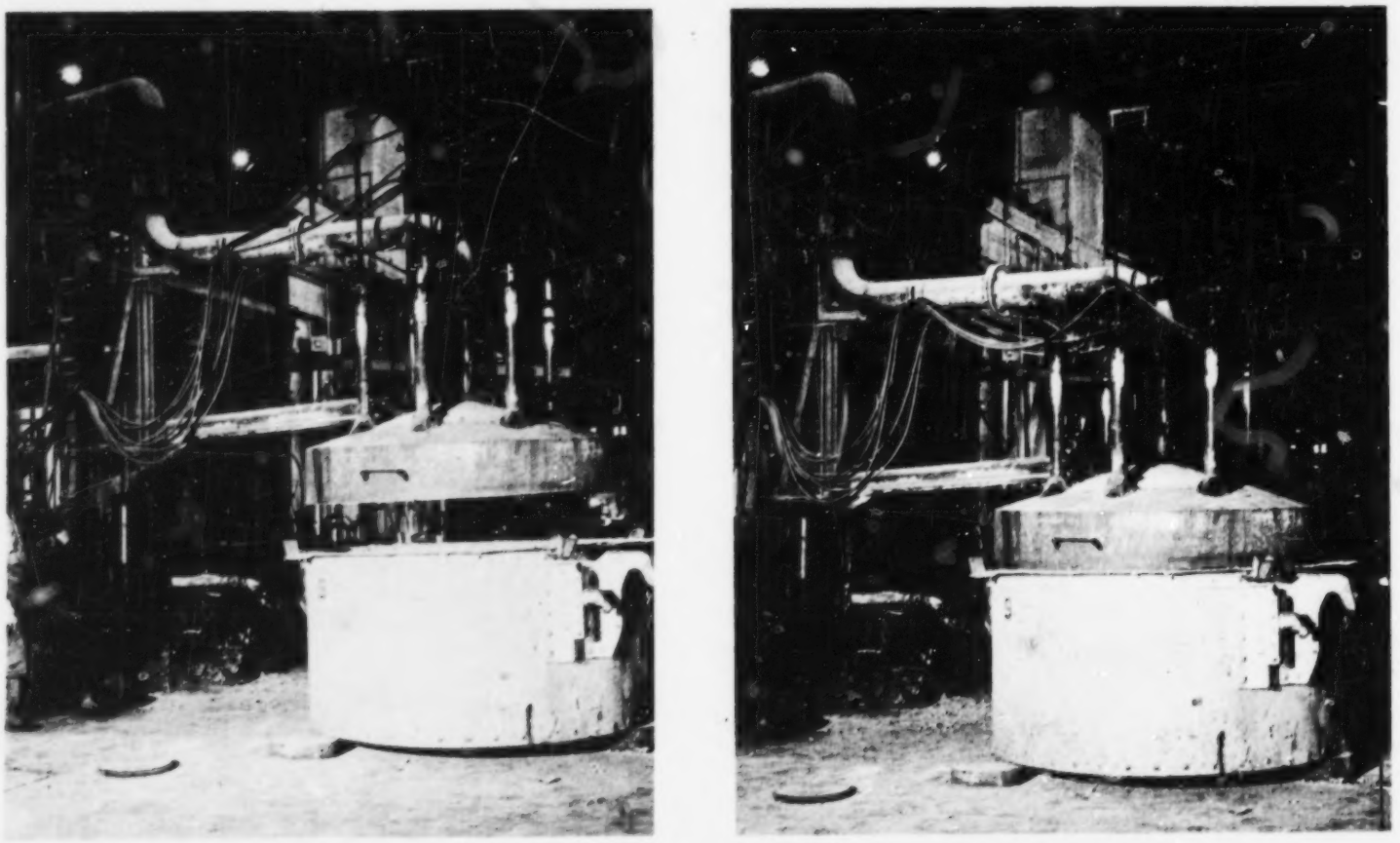


Figure 198. Ladle of molten aluminum with (left) lances in the raised position, and (right) hood in place and lances lowered into aluminum.

less magnesium, a greater fraction of the chlorine combines with the aluminum to form aluminum chloride ($AlCl_3$). The magnesium chloride melts at about 1,312°F, so that it is a liquid or solid at normal temperatures for this operation (about 1,300° to 1,350°F) and thus does not contribute significantly to the emissions. A very small amount may sometimes be released into the atmosphere as a result of mechanical entrainment. The aluminum chloride, on the other hand, sublimes at about 352°F, so that it is a vapor at the temperature of molten aluminum. As the vapors cool in the atmosphere, submicron fumes are formed, which have very great opacity in proportion to the weight of material involved.

Chlorine has a much greater affinity for magnesium than it has for aluminum. This is shown by the fact that alloys containing more than about 0.5 percent magnesium (and 90 to 97 percent aluminum) usually produce only a moderate quantity of fume in degassing with chlorine, while alloys with more than about 0.75 percent magnesium do not usually produce a significant quantity of fume.

In alloys with greater magnesium content, not only is less aluminum chloride formed, but also a thick layer of dross (largely magnesium chloride) is built up on the surface, which further suppresses the emission of fumes. Aluminum chloride also reacts with magnesium to form magnesium chloride and aluminum. The dross increases the opportunities for this latter reaction.

When chlorine is used for demagging, it is added so rapidly that large quantities of both aluminum chloride and magnesium chloride are formed, the molten bath is vigorously agitated, and not all of the chlorine reacts with the metals. As a result, a large quantity of aluminum chloride is discharged along with chlorine gas and some entrained magnesium chloride. The aluminum chloride is extremely hygroscopic and absorbs moisture from the air, with which it reacts to form hydrogen chloride. These air contaminants are toxic, corrosive, and irritating.

Particle Size of Fumes From Fluxing

One study (McCabe, 1952) found that the major constituent in the fume from salt-cryolite fluxing in a furnace was sodium chloride with considerable smaller quantities of compounds of aluminum and magnesium. Electron photomicrographs of thermal precipitator samples indicated that the particles of fume were all under 2 microns, most of them being 0.1 micron. The fumes were somewhat corrosive when dry and, when collected wet, formed a highly corrosive sludge that tended to set up and harden if allowed to stand for any appreciable time. Another study made of the fume from chlorinating aluminum to degas revealed that 100 percent of the fume was smaller than 2 microns and 90 to 95 percent smaller than 1 micron. Mean particle size appeared under a microscope to be about 0.7 micron.

HOODING AND VENTILATION REQUIREMENTS

When no charging well is provided, or when fluxing is done inside the furnace, or when dirty scrap is charged directly into the furnace, then venting the furnace may be necessary. In some cases, the products of combustion must be vented to the air pollution control equipment. The volume to be vented to the collector, and the determination of temperature may be found similarly to metallurgical furnace calculation procedures described elsewhere in this manual.

A canopy hood (as previously shown in Figure 197) is usually used for capturing the emissions from the charging well of an aluminum reverberatory furnace. Calculation of the quantity of air required can be accomplished as shown in the following example.

Example 29

Given:

Metal surface, 2 ft 3 in. x 11 ft 3 in.
Temperature of molten metal, 1,350°F.
Hood opening dimensions, 3 ft 9 in. x 13 ft 9 in.
Height of hood face above metal surface, 2 ft 6 in.
Ambient air temperature, 80°F.

Problem:

Determine the volume of air that must be vented from a low-canopy hood over the charging well of an aluminum-melting reverberatory furnace to ensure complete capture of the air contaminants.

Solution:

As discussed in Chapter 3, the following equation gives the total ventilation rate for low-canopy hoods:

$$q = 5.4\,(A)(m)^{1/3}\,(\Delta t)^{5/12}$$

where

q = total ventilation rate required, cfm

A = area of the hood face, ft^2

m = the width of the hot metal surface at the charging well, ft

Δt = the difference in temperature between the hot surface and the ambient air, °F.

$$q = (5.4)(3.75)(13.75)(2.25)^{1/3} \quad (1,350-80)^{5/12}$$

$$= 7,170 \text{ cfm}$$

Problem note: The volume calculated here is the minimum ventilation required just to accommodate the rising column of air due to the thermal drive. An additional allowance must be made to take care of drafts. If volatile fluxes are used, the volume of fumes generated must also be accommodated. In most cases an allowance of about 25 percent additional volume is adequate to ensure complete pickup. The exhaust system should therefore be designed to vent about 9,000 cfm.

Although the gases vented from the charging well are hot, sufficient air is drawn into the hood to preclude any danger that the hot gas will damage the exhaust system. The temperature of the mixed gas stream is calculated in example 30.

Example 30

Given:

The furnace with charging well and canopy hood venting 9,000 cfm as shown in Example 29.

Problem:

Determine the temperature of the air entering the hood.

Solution:

1. Determine the heat transferred from the hot metal surface to the air by natural convection:

From Chapter 3, $H' = \dfrac{h_c A_s \Delta t}{60}$

where

H' = heat transferred from hot metal surface to the air by natural convection, Btu/min

h_c = coefficient of heat transfer from horizontal plates by natural convection, Btu/hr/ft^2/°F

A_s = area of hot metal surface, ft^2

Δt = temperature difference between hot metal surface and ambient air, °F.

By using $h_c = 0.38\ (\Delta t)^{0.25}$ and substituting this quantity into the equation,

$$H' = \frac{0.38\ (A_s)(\Delta t)^{1.25}}{60}$$

$$H' = \frac{(0.38)(2.25)(11.25)(1,350-80)^{1.25}}{60}$$

$$= 1,210 \text{ Btu/min}$$

2. Solve for temperature of the air entering the hood (assume specific volume of air = 13.8 ft^3/lb):

$$q = W c_p \Delta t$$

where c_p = specific heat of air at constant pressure.

$$\Delta t = \frac{(1,210)(13.8)}{(9,000)(0.24)} = 7.7°F$$

Temperature of air entering the hood = 80 + 7.7 = 87.7°F.

The actual temperature of the air entering the hood will be slightly higher than the value calculated here, owing to radiation from the molten metal surface, and radiation and convection from the hood and the furnace. In some cases, when the burners are operated at maximum capacity, there may be a positive pressure in the furnace. If the design of the furnace permits some of the products of combustion to be vented into the hood, the actual temperature may be substantially higher than shown here. This situation would also require venting a greater volume to ensure capturing the emissions.

AIR POLLUTION CONTROL EQUIPMENT

The emissions from aluminum fluxing may consist of hydrogen fluoride, hydrogen chloride, and chlorine in a gaseous state, and aluminum chloride, magnesium chloride, aluminum fluoride, magnesium fluoride, aluminum oxide, magnesium oxide, zinc chloride, zinc oxide, calcium fluoride, calcium chloride, and sodium chloride in the solid state. Not all will be present at one time, and many other, minor contaminants may be emitted in a specific case. Because of the widely divergent properties of these various air contaminants, the problem of control is complicated.

Some type of scrubber is required to remove the soluble gaseous fraction of the effluent, and either a baghouse or an electrical precipitator is needed to control the solids. In order to obtain adequate collection efficiency, the use of high-efficiency scrubbers, with a caustic solution as the scrubbing medium, has been found necessary. This is illustrated in Table 83, which shows typical test data on collection efficiency for both ordinary and high-efficiency scrubbers.

Table 83. SCRUBBER COLLECTION EFFICIENCY FOR EMISSIONS FROM CHLORINATING ALUMINUM

Scrubber collection efficiencies, %[a]				
	Slot scrubber		Packed-column scrubber	
Contaminants	Water	10% caustic solution	Water	10% caustic solution
HCL	90 to 95	95 to 99	95 to 98	99 to 100
CL_2	30 to 50	50 to 60	75 to 85	90 to 95
Particulates	30 to 50	50 to 60	70 to 80	80 to 90

[a]Collection efficiency depends mainly upon scrubbing ratio (gal per 1,000 ft^3), velocity of gas in scrubber, and contact time and to a lesser extent on other aspects of the design. These values are typical efficiencies obtained by actual tests but do not reflect the entire range of results.

Table 84 summarizes the results of a series of 200 tests made of control efficiencies of nine devices by a major producer of aluminum (Jenny, 1951). These results represent the average range of efficiencies for a number of tests but are not necessarily the maximum or minimum values obtained. In spite of the high efficiencies obtained with some of these devices, reducing the emissions sufficiently to eliminate a visible plume was very difficult. For the dry ultrasonic unit, the opacity of the emissions exceeded 40 percent when the outlet grain loading was greater than 0.25 grain per cubic foot. The efficiency of this unit varied widely with the inlet grain loading and retention time, the efficiency increasing with increasing values of either or both of these variables. Other tests by the same company on collectors of a wet type revealed that the opacity exceeded 40 percent periodically, even when the average grain loading at the vent was as low as 0.002 grain per cubic foot.

Table 84. AVERAGE COLLECTION EFFICIENCY OBTAINED BY VARIOUS DEVICES ON EMISSIONS FROM CHLORINATING ALUMINUM (Jenny, 1951)

Type of device	Efficiency, %
Horizontal multipass wet cyclone	65 to 75
Single-pass wet dynamic collector	70 to 80
Packed-column water scrubber with limestone packing	75 to 85
Ultrasonic agglomerator followed by a multitube dry cyclone	85 to 98
Electrical precipitator	90 to 99

Figures 198, 199, and 200 show parts of a single installation of air pollution control equipment for the control of emissions from chlorinating aluminum. One of the three stations where chlorinating is performed is shown in Figure 198. Note that the hooding closely encloses the source so that a minimum volume of air is required to attain 100 percent pickup of air contaminants. The fumes are scrubbed in the packed-column scrubbers shown in Figure 199. This system was designed to use two of the three scrubbers in parallel, with the third as a standby. The scrubbing medium is a 10 percent caustic solution. After the scrubbing, the effluent is vented to a five-compartment baghouse with a fully automatic shaking mechanism to remove residual particulate matter. The baghouse contains a total of 300 orlon bags with a net filtering area of 12,000 square feet. In addition to the fumes from chlorine fluxing, which are vented through the scrubbers, two aluminum dross-processing barrels (Figure 200) are vented directly to the baghouse. The total volume handled by the baghouse is about 30,000 cfm, of which

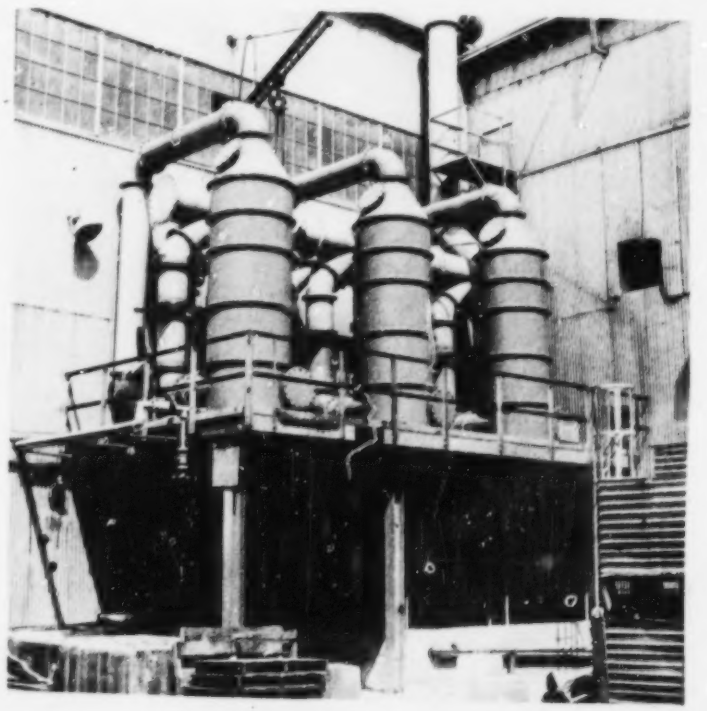


Figure 199. High-efficiency packed-column water scrubbers used with a baghouse for control of emissions from chlorine fluxing and dross processing.

approximately 6,000 cfm is from the three chlorine fluxing stations and the balance from the two dross barrel hoods. The beneficial effect of the bag precoating provided by the aluminum oxide dust vented from the dross-processing barrels permits a much higher filtering velocity than would be advisable if only the fluxing stations were being served by the baghouse.

Tests of the scrubber performance have shown that virtually all the hydrogen chloride and more than 90 percent of the chlorine are removed by the caustic scrubbing solution. Since the efficiency of aluminum chloride removal averages in excess of 80 percent, the loading of hygroscopic and corrosive materials to the baghouse is relatively light. The aluminum oxide dust from the dross barrels acts as a filter cake, which improves the collection efficiency of the aluminum chloride fume while simultaneously reducing or eliminating the difficulties usually associated with collecting hygroscopic materials. All exposed metal parts are coated with polyvinyl chloride or other appropriate protective coatings. The first year of operation indicates that no serious operational or maintenance problems will develop. This installation replaced an electrical precipitator that was found extremely difficult and expensive to maintain because of corrosion.

An electrical precipitator that has been used successfully to control the emissions from fluxing aluminum is illustrated in Figure 201. At present the trend in control equipment for aluminum-fluxing emissions appears to be away from electrical precipitators and toward the scrubber-baghouse combination.

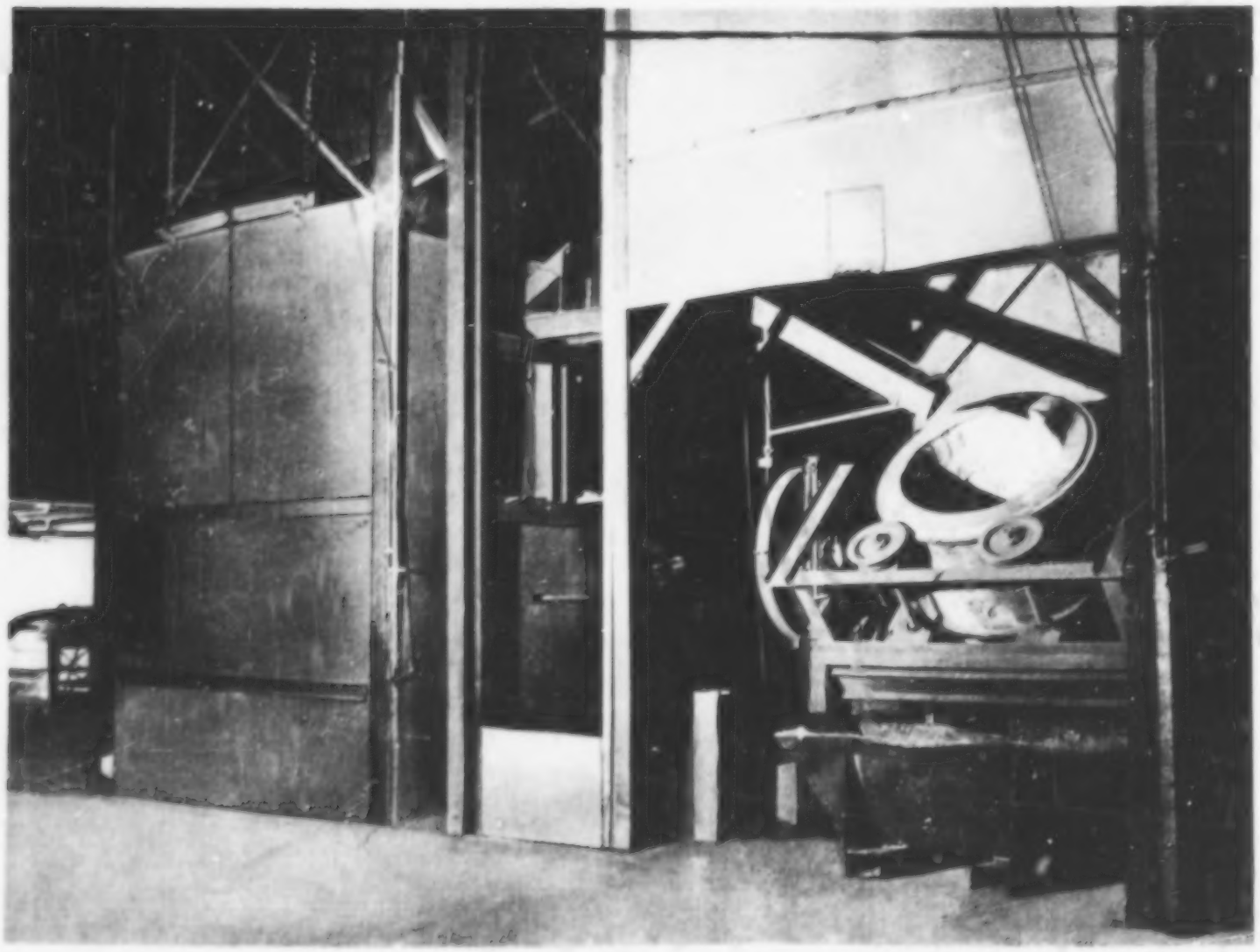


Figure 200. Two aluminum dross-processing stations, one shown with hood door raised.

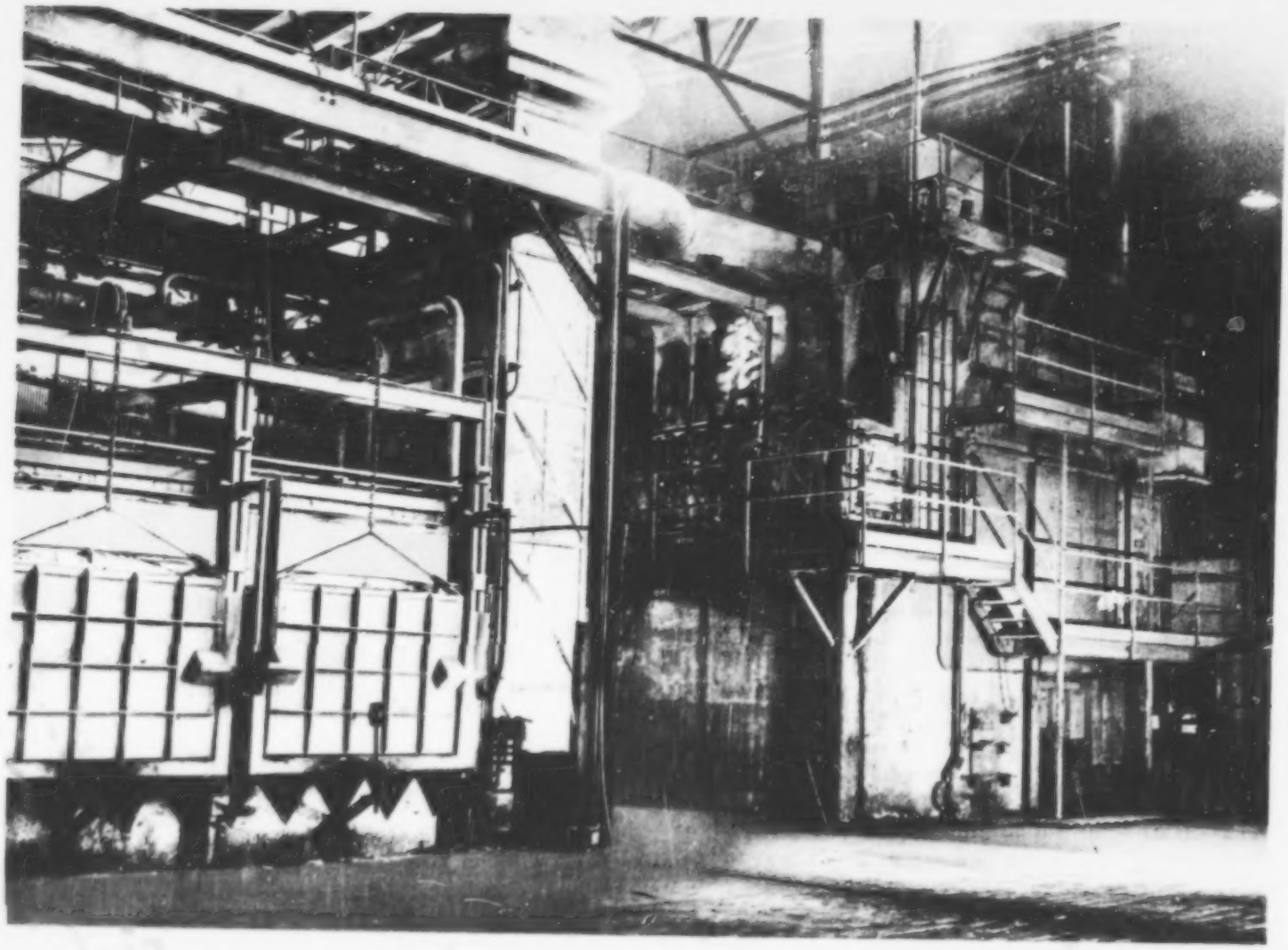


Figure 201. Concrete shell-type electrical precipitator used for controlling emissions from fluoride fluxing aluminum metal. The reverberatory furnace is shown in the left portion of the photograph (Apex Smelting Co., Long Beach, Calif.).

SECONDARY ZINC-MELTING PROCESSES

Zinc is melted in crucible, pot, kettle, reverberatory, or electric-induction furnaces for use in alloying, casting, and galvanizing and is reclaimed from higher melting point metals in sweat furnaces. Secondary refining of zinc is conducted in retort furnaces, which can also be used to manufacture zinc oxide by vaporizing and burning zinc in air. All these operations will be discussed in this section except the reclaiming of zinc from other metals by use of a sweat furnace. Information on this subject can be found in a following section entitled, "Metal Separation Processes."

ZINC MELTING

The melting operation is essentially the same in all the different types of furnaces. In all but the low-frequency induction furnace, solid metal can be melted without the use of a molten heel. Once a furnace is started, however, a molten heel is generally retained after each tap for the beginning of the next heat.

Zinc to be melted may be in the form of ingots, reject castings, flashing, or scrap. Ingots, rejects, and heavy scrap are generally melted first to provide a molten bath to which light scrap and flashing are added. After sufficient metal has been melted, it is heated to the desired pouring temperature, which may vary from 800° to 1,100°F. Before the pouring, a flux is added and the batch agitated to separate the dross accumulated during the melting operation. Dross is formed by the impurities charged with the metal and from oxidation during the melting and heating cycles. The flux tends to float any partially submerged dross and conditions it so that it can be skimmed from the surface. When only clean ingot is melted, very little, if any, fluxing is necessary. On the other hand, if dirty scrap is melted, large amounts of fluxes are needed. After the skimming, the melt is ready for pouring

into molds or ladles. No fluxing or special procedures are employed while the zinc is being poured.

The Air Pollution Problem

The discharge of air contaminants from melting furnaces is generally caused by excessive temperatures and by the melting of metal contaminated with organic material. Fluxing can also create excessive emissions, but fluxes are available that clean the metal without fuming.

Probably the first visible discharge noted from a furnace is from organic material. Before the melt is hot enough to vaporize any zinc, accompanying organic material is either partially oxidized or vaporized, causing smoke or oily mists to be discharged. This portion of the emissions can be controlled either by removing the organic material before the charging to the furnace or by completely burning the effluent in a suitable incinerator or afterburner.

Normally, zinc is sufficiently fluid for pouring at temperatures below 1,100°F. At that temperature, its vapor pressure is 15.2 millimeters of mercury, low enough that the amount of fumes formed cannot be seen. If the metal is heated above 1,100°F, excessive vaporization can occur and the resulting fumes need to be controlled with an air pollution control device. Zinc can vaporize and condense as metallic zinc if existing temperatures and atmospheric conditions do not promote oxidation. Finely divided zinc so formed is a definite fire hazard, and fires have occurred in baghouses collecting this material.

Many fluxes now in use do not fume, and air contaminants are not discharged. In some cases, however, a specific fuming flux may be needed, in which case a baghouse is required to collect the emissions. An example of a fuming flux is ammonium chloride, which, when heated to the temperature of molten zinc, decomposes into ammonia and hydrogen chloride gases. As the gases rise into the atmosphere above the molten metal, they recombine, forming a fume consisting of very small particles of ammonium chloride.

Provided the temperature of the melt does not exceed 1,100°F, there should be no appreciable amounts of air contaminants discharged when the zinc is poured into molds. Some molds, however, especially in die casting, are coated with mold release compounds containing oils or other volatile material. The heat from the metal vaporizes the oils, creating air contaminants. Recently mold release compounds have been developed that do not contain oils, and this source of air pollution is thereby eliminated.

ZINC VAPORIZATION

Retort furnaces are used for operations involving the vaporization of zinc including (1) reclaiming zinc from alloys, (2) refining by distillation, (3) recovering zinc from its oxide, (4) manufacturing zinc oxide, and (5) manufacturing powdered zinc.

Three basic types of retort furnaces are used in Los Angeles County: (1) Belgian retorts, (2) distillation retorts (sometimes called bottle retorts), and (3) muffle furnaces. Belgian retorts are used to reduce zinc oxide to metallic zinc. Distillation retorts, used for batch distillations, reclaim zinc from alloys, refine zinc, make powdered zinc, and make zinc oxide. Muffle furnaces, used for continuous distillation, reclaim zinc from alloys, refine zinc, and make zinc oxide.

Although zinc boils at 1,665°F, most retort furnaces are operated at temperatures ranging from 1,800° to 2,280°F. Zinc vapor burns spontaneously in air; therefore, air must be excluded from the retort and condenser when metallic zinc is the desired product. Condensers are designed, either for rapid cooling of the zinc vapors to a temperature below the melting point to produce powdered zinc, or for slower cooling to a temperature above the melting point to produce liquid zinc. When the desired product is zinc oxide, the condenser is bypassed and the vapor is discharged into a stream of air where spontaneous combustion converts the zinc to zinc oxide. Excess air is used, not only to ensure sufficient oxygen for the combustion, but also to cool the products of combustion and convey the oxide to a suitable collector.

REDUCTION RETORT FURNACES

Reduction in Belgian Retorts

The Belgian retort furnace is one of several horizontal retort furnaces that have been for many years the most common device for the reduction of zinc. Although the horizontal retort process is now being replaced by other methods capable of handling larger volumes of metal per retort and by the electrolytic process for the reduction of zinc ore, only Belgian retorts are used in the Los Angeles area. In this area, zinc ores are not reduced; the reduction process is used to reclaim zinc from the dross formed in zinc-melting operations, the zinc oxide collected by air pollution control systems serving zinc alloy-melting operations, and the contaminated zinc oxide from zinc oxide plants.

A typical Belgian retort (Figure 202) is about 8 inches in internal diameter and from 48 to 60 inches long. One end is closed and a conical shaped

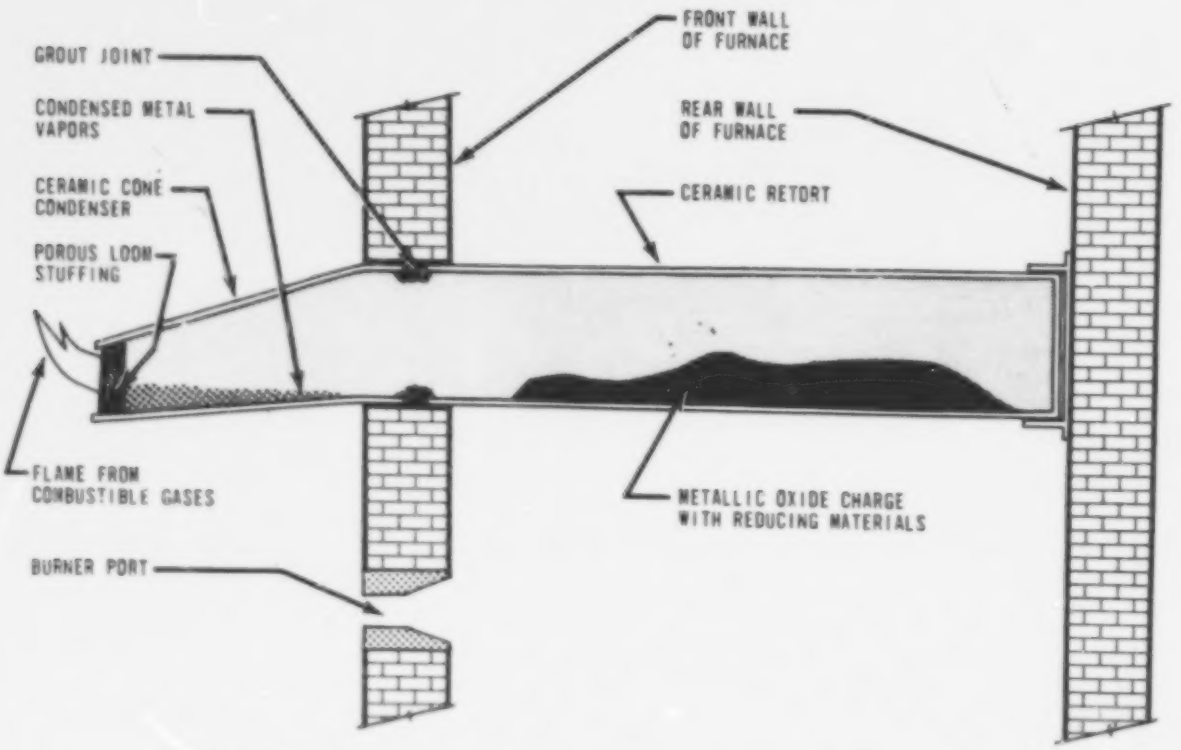


Figure 202. Diagram showing one bank of a Belgian retort furnace.

clay condenser from 18 to 24 inches long is attached to the open end. The retorts are arranged in banks with rows four to seven high and as many retorts in a row as are needed to obtain the desired production. The retorts are generally gas fired.

The retorts are charged with a mixture of zinc oxide and powdered coke. Since these materials are powdered, water is added to facilitate charging and allow the mixture to be packed tightly into the retort. From three to four times more carbon is used than is needed for the reduction reaction.

After the charging, the condensers are replaced and their mouths stuffed with a porous material. A small hole is left through the stuffing to allow moisture and unwanted volatile materials to escape. About 3 hours are needed to expel all the undesirable volatile materials from the retort. About 6 hours after charging is completed, zinc vapors appear. The charge in the retort is brought up to 1,832° to 2,012°F for about 8 hours, after which it may rise slowly to a maximum of 2,280°F. The temperature on the outside of the retorts ranges from 2,375° to 2,550°F. The condensers are operated at from 780° to 1,020°F, a temperature range above the melting point of zinc but where the vapor pressure is so low that a minimum of zinc vapor is lost.

The reduction reaction of zinc oxide can be summarized by the reaction:

$$ZnO + C = Zn + CO \qquad (101)$$

Very little, if any, zinc oxide is, however, actually reduced by the solid carbon in the retort. A series of reactions results in an atmosphere rich in carbon monoxide, which does the actual reducing. The reactions are reversible, but by the use of an excess of carbon, they are forced toward the right. The reactions probably get started by the oxidation of a small portion of the coke by the oxygen in the residual air in the retort. The oxygen is quickly used, but the carbon dioxide formed reacts with the carbon to form carbon monoxide according to the equation:

$$CO_2 + C = 2CO \qquad (102)$$

The carbon monoxide in turn reacts with zinc oxide to produce zinc and carbon dioxide:

$$CO + ZnO = Zn + CO_2 \qquad (103)$$

Carbon monoxide is regenerated by use of equation 102, and the reduction of the zinc oxide proceeds.

About 8 hours after the first zinc begins to be discharged, the heat needed to maintain production begins to increase and the amount of zinc produced begins to decrease. Although zinc can still be produced, the amount of heat absorbed by the reduction reaction decreases and the temperature of the retort and its contents increases. Care must be taken not to damage the retort or fuse its charge. As a result, a 24-hour cycle has been found to be an economical operation. The zinc values still in the spent charge are recovered by recycling with the fresh charges. A single-pass

recovery yields 65 to 70 percent of the zinc charged, but, by recycling, an overall recovery of 95 percent may be obtained.

The Air Pollution Problem

The air contaminants emitted vary in composition and concentration during the operating cycle of Belgian retorts. During charging operation very low concentrations are emitted. The feed is moist and, therefore, not dusty. As the retorts are heated, steam is emitted. After zinc begins to form, both carbon monoxide and zinc vapors are discharged. These emissions burn to form gaseous carbon dioxide and solid zinc oxide. During the heating cycle, zinc is poured from the condensers about three times at 6- to 7-hour intervals. The amount of zinc vapors discharged increases during the tapping operation. Before the spent charge is removed from the retorts, the temperature of the retorts is lowered, but zinc fumes and dust from the spent charge are discharged to the atmosphere.

Hooding and Ventilation Requirements

Air contaminants are discharged from each retort. In one installation, a furnace has 240 retorts arranged in five horizontal rows with 48 retorts per row. The face of the furnace measures 70 feet long by 8 feet high; therefore, the air contaminants are discharged from 240 separate openings and over an area of 560 square feet. A hood 2 feet wide by 70 feet long positioned immediately above the front of the furnace is used to collect the air contaminants. The hood indraft is 175 fpm.

DISTILLATION RETORT FURNACES

The distillation retort furnace (Figure 203) consists of a pear-shaped, graphite retort, which may be 5 feet long by 2 feet in diameter at the closed end by 1-1/2 feet in diameter at the open end and 3 feet in diameter at its widest cross-section. Normally, the retort is encased in a brick furnace with only the open end protruding and it is heated externally with gas- or oil-fired burners. The retorts are charged with molten, impure zinc through the open end, and a condenser is attached to the opening to receive and condense the zinc vapors. After the distillation is completed, the condenser is moved away, the residue is removed from the retort, and a new batch is started.

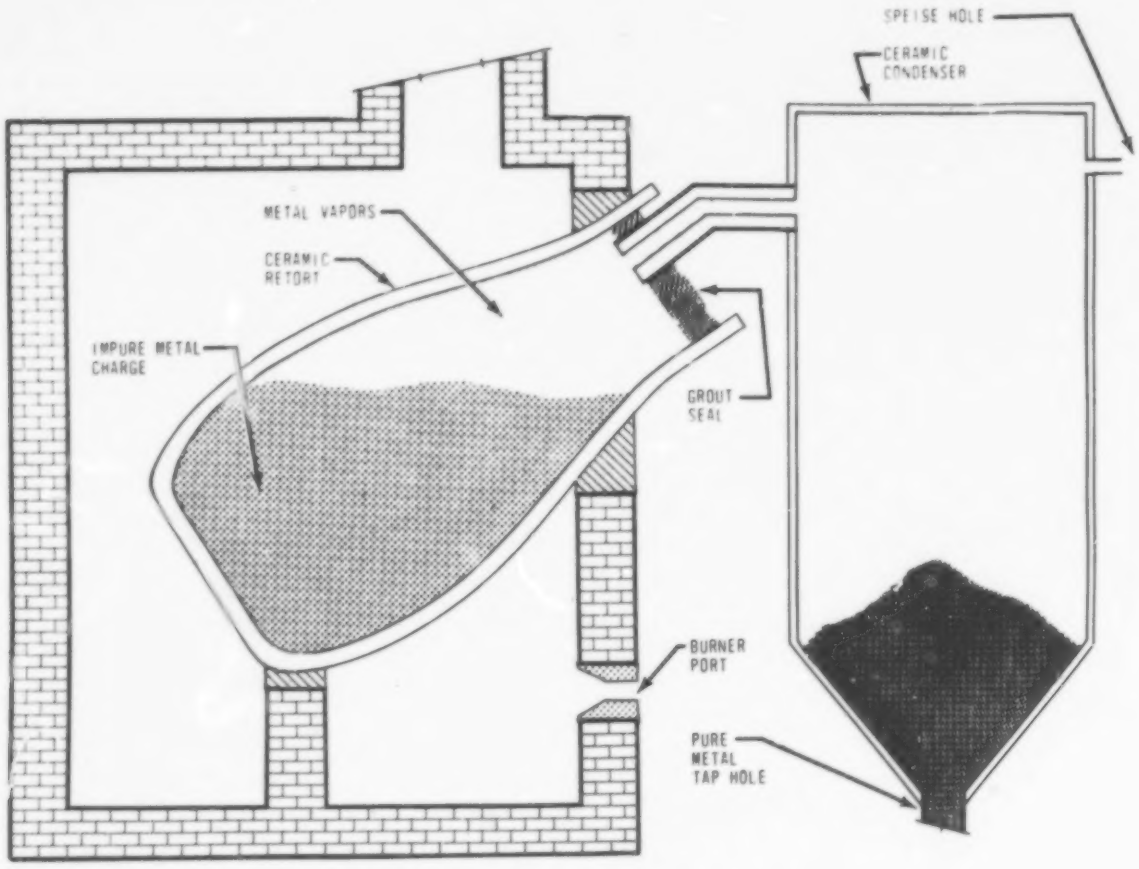


Figure 203. Diagram of a distillation-type retort furnace.

The vaporized zinc is conducted either to a condenser or discharged through an orifice into a stream of air. Two types of condenser are used--a brick-lined steel condenser operated at from 780° to 1,012°F to condense the vapor to liquid zinc, or a larger, unlined steel condenser that cools the vapor to solid zinc. The latter condenser is used to manufacture powdered zinc. The condensers must be operated at a slight positive pressure to keep air from entering them and oxidizing the zinc. To ensure that there is a positive pressure, a small hole, called a "speise" hole, is provided through which a small amount of zinc vapor is allowed to escape continuously into the atmosphere. The vapor burns with a bright flame, indicating that there is a pressure in the condenser. If the flame gets too large, the pressure is too high. If it goes out, the pressure is too low. In either case, the proper adjustments are made to obtain the desired condenser pressure.

When it is desired to make zinc oxide, the vapor from a retort is discharged through an orifice into a stream of air where zinc oxide is formed inside a refractory-lined chamber. The combustion gases and air, which bear the oxide particles, are then carried to a baghouse collector where the powdered oxide is collected.

The Air Pollution Problem

During the 24-hour cycle of the distillation retorts, zinc vapors escape from the retort (1) when the residue from the preceding batch is removed from the retort and a new batch is charged, and (2) when the second charge is added to the retort. As the zinc vapors mix with air, they oxidize and form a dense cloud of zinc oxide fumes. Air contaminants are discharged for about 1 hour each time the charging hole is open. When the zinc is actually being distilled, no fumes escape from the retort; however, a small amount of zinc oxide escapes from the speise hole in the condenser. Although the emission rate is low, air contaminants are discharged for about 20 hours per day.

Hooding and Ventilation Requirements

To capture the emissions from a distillation retort furnace, simple canopy hoods placed close to and directly over the sources of emissions are sufficient. In the only installation in Los Angeles County, the charging end of the retort protrudes a few inches through a 4-foot-wide, flat wall of the furnace. The hood is 1 foot above the retort, extends 1-1/4 feet out from the furnace wall, and is 4 feet wide. The ventilation provided is 2,000 cfm, giving a hood indraft of 400 fpm. Fume pickup is excellent. The speise hole is small and all the fumes discharged are captured by a 1-foot-diameter hood provided with 200 cfm ventilation. The hood indraft is 250 fpm.

The retorts are gas fired and the products of combustion do not mix with the emissions from the retort or the condenser. The exhausted gases are heated slightly by the combustion of zinc and from radiation and convection losses from the retort, but the amount of heating is so low that no cooling is necessary.

MUFFLE FURNACES

Muffle furnaces (Figure 204) are continuously fed retort furnaces. They generally have a much greater vaporizing capacity than either Belgian retorts or bottle retorts do, and they are operated continuously for several days at a time. Heat for vaporization is supplied by gas- or oil-fired burners by conduction and radiation through a silicon carbide arch that separates the zinc vapors and the products of combustion. Molten zinc from either a melting pot or sweat furnace is charged through a feed well that also acts as an air lock. The zinc vapors are conducted to a condenser where purified liquid zinc is collected, or the condenser is bypassed and the vapors are discharged through an orifice into a stream of air where zinc oxide is formed.

A muffle furnace installation in Los Angeles County consists of three identical furnaces, each capable of vaporizing several tons of zinc per day. These furnaces can produce zinc of 99.99 percent purity and zinc oxide of 99.95 percent purity from zinc alloys. Each furnace has three sections: (1) A vaporizing chamber, (2) a condenser, and (3) a sweating chamber. Figure 205 shows the feed ends of the furnaces, including the sweating chambers, and some of the ductwork and hoods serving the furnaces.

Each furnace, including the feed well and sweating chamber, is heated indirectly with a combination gas- or oil-fired burner. The combustion chamber, located directly over the vaporizing chamber, is heated to about 2,500°F. On leaving the combustion chamber, the products of combustion are conducted over the zinc feed well and through the sweating chamber to supply the heat needed for melting the zinc alloys from the scrap charged and for heating the zinc in the feed well to about 900°F.

Zinc vapors are conducted from the vaporizing section into a multiple-chamber condenser. When zinc oxide is the desired product, the vapors are allowed to escape through an orifice at the top of the first chamber of the condenser. Even when maximum zinc oxide production is desired, some molten zinc is nevertheless formed and collects in the condenser.

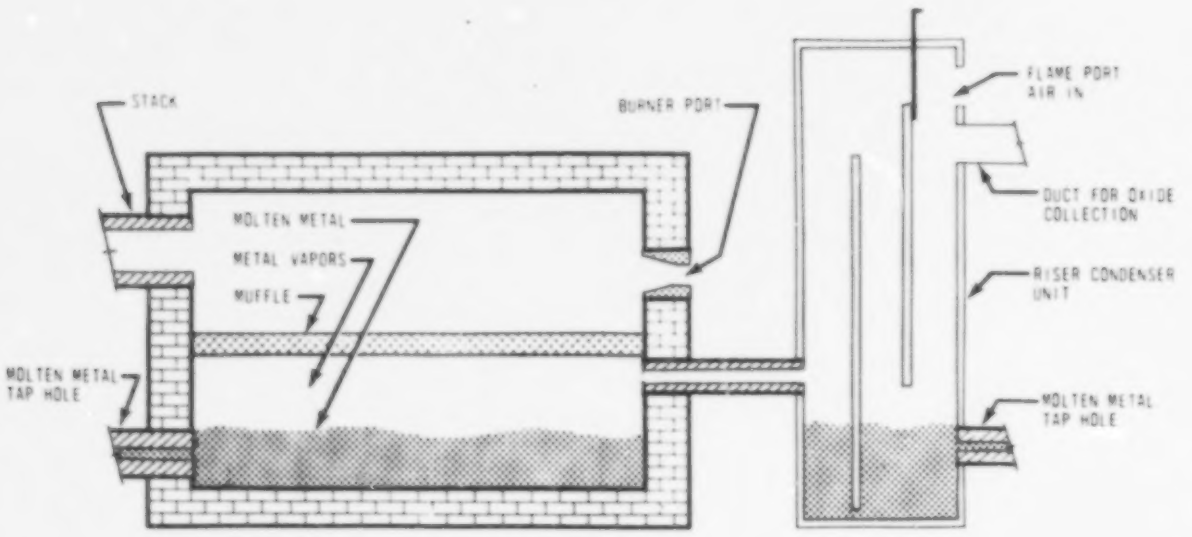


Figure 204. Diagram of a muffle furnace and condenser.

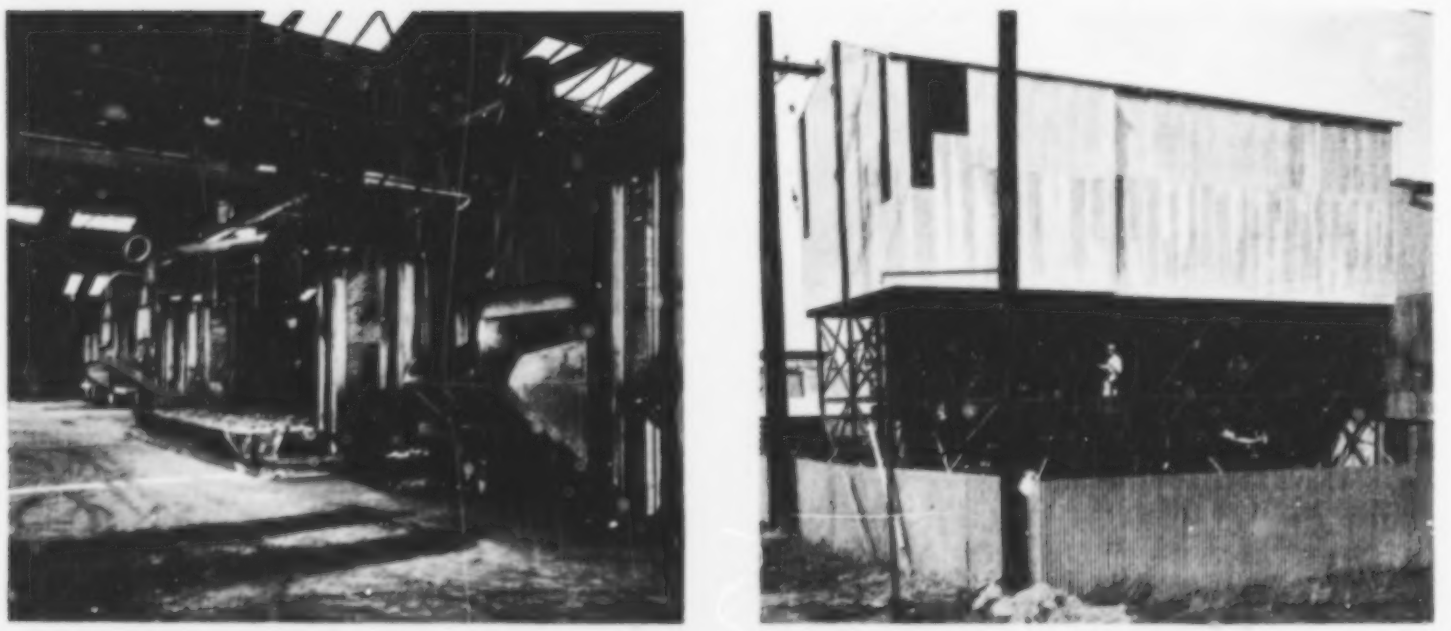


Figure 205. (Left) Zinc-vaporizing muffle furnaces, (right) baghouse for collecting the zinc oxide manufactured (Pacific Smelting Co., Torrance, Calif.).

When metallic zinc is the desired product, the size of the orifice is greatly reduced, but not entirely closed, so that most of the vapors enter the second section of the condenser where they condense to molten zinc. The molten zinc collected in the condenser is held at about 900°F in a well, from which it is periodically tapped. The well and the tap hole are so arranged that sufficient molten zinc always remains in the well to maintain an air lock.

The zinc that escapes from the orifice while molten zinc is being made burns to zinc oxide, which is conducted to the product baghouse.

The Air Pollution Problem

Dust and fumes are created by the sweating operation. Scrap is charged into the sweating chamber through the door shown in Figure 205. After the

zinc alloys have been melted, the residue is pushed out of the chamber through a second door and onto a shaker screen where dross is separated from solid metal. Excessive dust and fumes are thereby created.

The zinc alloys charged into the vaporizing section contain copper, aluminum, iron, lead, and other impurities. As zinc is distilled from the metals, the concentration of the impurities increases until continued distillation becomes impractical. After 10 to 14 days of operation, the residue, containing 10 to 50 percent zinc must be removed. When tapped, the temperature of the residue is about 1,900°F, hot enough to release zinc oxide fumes. The molds collecting the residue metal are so arranged that the metal overflows from one mold to another; however, the metal cools so rapidly that fumes are released only from the pouring spout and the first two or three molds. The fumes, almost entirely zinc oxide, are 100 percent opaque from the pouring spout and the first mold. At the third mold, the opacity decreases to 10 percent.

Any discharge of zinc vapor from the condenser forms zinc oxide of product purity; therefore, the condenser vents into the intake hood of a product-collecting exhaust system. Since some zinc oxide is always produced, even when the condenser is set to produce a maximum of liquid zinc, the product-collecting exhaust system is always in operation to prevent air contaminants from escaping from the condenser to the atmosphere.

Hooding and Ventilation Requirements

The dust and fumes created by the charging of scrap and the sweating of zinc alloys from the scrap originate inside the sweat chamber. The thermal drafts cause the emissions to escape from the upper portion of the sweat chamber doors. Hoods are placed over the doors to collect the emissions. The charging door hood extends 10 inches from the furnace wall and covers a little more than the width of the door (see Figure 205). With two furnaces in operation at the same time, each of the charging door hoods is supplied with 3,200 cfm ventilation, which provides an indraft velocity of 700 fpm. All fumes escaping from the charging doors are collected by these hoods.

The unmelted scrap and dross are raked from a sweating chamber onto a shaker screen. A hood enclosing the discharge lip and the screen is provided with 5,500 cfm ventilation. The inlet velocity is 250 fpm, sufficient to capture all of the emissions escaping from both the furnace and the screen.

A hood 3 feet square positioned over the residue metal-tapping spout and the first mold is provided with 8,700 cfm ventilation. During the tapping, no metal is charged to either sweating chamber, and the exhaust system dampers are arranged so that approximately one-half of the available volume is used at the tapping spout. The indraft velocity is in excess of 900 fpm, and all fumes released from the metal are collected, even from the second and third molds up to 6 feet away from the hood.

The ductwork joining the hoods to the control devices is manifolded and dampered so that any or all hoods can be opened or closed. The exhaust system provides sufficient ventilation to control the fumes created by two furnaces in operation at the same time. When residue metal is being tapped from a furnace, no metal is being charged to the other furnaces; therefore, all the ventilation, or as much as is needed, can be used at the tapping hood.

AIR POLLUTION CONTROL EQUIPMENT

For all the furnaces mentioned in this section, that is reduction retort furnaces, distillation retort furnaces, and muffle furnaces, air pollution control is achieved with a baghouse. In the above-mentioned installation for a muffle furnace, a low-efficiency cyclone and a baghouse are used to control the emissions from the sweating chambers and residue pouring operations of the three muffle furnaces. Although the cyclone has a low collection efficiency, it does collect from 5 to 10 percent of the dust load and it is still used. The cyclone was in existence before the baghouse was installed.

The baghouse is a six-section, pull-through type using 5,616 square feet of glass cloth filtering area. The filtering velocity is 3 fpm and the bags are cleaned automatically at regular intervals by shutting off one section, which allows the bags to collapse. No shaking is required, and the collected material merely drops into the hopper below the bags.

Another exhaust system with a cyclone and baghouse is used to collect the zinc oxide manufactured by the muffle furnaces. The system has three inlet hoods, one for each furnace, and each is arranged to collect the zinc vapors discharged from the orifice in the condenser. The ductwork is manifolded into a single duct entering the cyclone, and dampers are provided so that any one or any combination of the hoods can be used at one time. Since the exhausted gases and zinc oxide are heated by the combustion of zinc and by the sensible heat in the zinc, about 350 feet of additional ductwork is provided to allow the ex-

hausted material to cool down to 180°F before entering the baghouse.

The cyclone collects about 20 percent of the solid materials in the exhaust gases, including all the heavier particles such as vitrified zinc oxide and solid zinc. The baghouse collects essentially all the remaining 80 percent of the solids.

The baghouse collector is actually two standard nine-section baghouses operating in parallel. In this unit, orlon bags with a total of 16,848 square feet of filtering area are used to filter the solids from the gases. A 50-hp fan provides 30,500 cfm ventilation--15,250 cfm for each furnace. The filtering velocity is 1.8 fpm. The bags are cleaned at regular intervals by shutting off one section and shaking the bags for a few seconds. A screw conveyor in the bottom of each hopper conveys the zinc oxide collected to a bagging machine.

This system provides excellent ventilation for the installation. None of the zinc oxide discharging from the condensers escapes collection by the hoods, and no visible emissions can be seen escaping from the baghouse.

Dust collectors for other zinc-melting and zinc-vaporizing furnaces are very similar to the ones already described. Glass bags have been found adequate when gas temperatures exceed the limits of cotton or orlon. Filtering velocities of 3 fpm are generally employed and have been found adequate.

LEAD REFINING

Control of the air pollution resulting from the secondary smelting and reclaiming of lead scrap may be conveniently considered according to the type of furnace employed. The reverberatory, blast, and pot furnaces are the three types most commonly used. In addition to refining lead, most of the secondary refineries also produce lead oxide by the Barton process.

Various grades of lead metal along with the oxides are produced by the lead industry. The grade of product desired determines the type of equipment selected for its manufacture. The most common grades of lead produced are soft, semisoft, and hard. By starting with one of these grades and using accepted refining and alloying techniques, any special grade of lead or lead alloy can be made.

Soft lead may be disignated as corroding, chemical, acid copper, or common desilverized lead. These four types are high-purity leads. Their chemical requirements are presented in Table 85. These leads are the products of the pot furnace after a considerable amount of refining has been done.

Semisoft lead is the product of the reverberatory-type furnace and usually contains from 0.3 to 0.4 percent antimony and up to 0.05 percent copper.

Hard lead is made in the blast furnace. A typical composition for hard lead is 5 to 12 percent antimony, 0.2 to 0.6 percent arsenic, 0.5 to 1.2 percent tin, 0.05 to 0.15 percent copper, and 0.001 to 0.01 percent nickel.

REVERBERATORY FURNACES

Sweating operations are usually conducted in a reverberatory-type furnace or tube. This type of operation is discussed later in this chapter in a section on "Metal Separation Processes." The reverberatory furnace is also used to reclaim lead from oxides and drosses. Very often material for both sweating and reducing such as lead scrap, battery plates, oxides, drosses, and lead residues are charged to a reverberatory furnace. The charges are made up of a mixture of these materials and put into the furnace in such a manner as to keep a very small mound of unmelted material on top of the bath. As the mound becomes molten, more material is charged. This type of furnace may be gas fired or oil fired, or a combination of both. The temperature is maintained at approximately 2,300°F. Only sufficient draft is pulled to remove the smoke and fumes and still allow the retention of as much heat as possible over the hearth. The molten metal is tapped off at intervals as a semisoft lead as the level of the metal rises. This operation is continuous, and recovery is generally about 10 to 12 pounds of metal per hour per square foot of hearth area.

The Air Pollution Problem

A fairly high percentage of sulfur is usually present in various forms in the charge to the reverberatory furnace. The temperature maintained is sufficiently high to "kill" the sulfides and results in the formation of sulfur dioxide and sulfur trioxide in the exit gases. Also present in the smoke and fumes produced are oxides, sulfides, and sulfates of lead, tin, arsenic, copper, and antimony. An overall material balance shows on the product side approximately 47 percent recovery of metal, 46 percent recovery of slag sometimes called "litharge," and 7 percent of smoke and fumes.

The unagglomerated particulate matter emitted from secondary lead-smelting operations has been found to have a particle size range from 0.07 to 0.4 micron with a mean of about 0.3 micron (Allen et al., 1952). Figure 206 shows electron photo-

Table 85. CHEMICAL REQUIREMENTS FOR LEAD[a]
(ASTM Standards, Part 2, 1958)

	Corroding lead	Chemical lead	Acid-copper lead	Common desilverized lead
Silver, max %	0.0015	0.020	0.002	0.002
Silver, min. %		0.002		
Copper, max %	0.0015	0.080	0.080	0.0025
Copper, min. %		0.040	0.040	
Silver and copper together, max %	0.0025		0.040	
Arsenic, antimony, and tin together, max %	0.002	0.002	0.002	0.005
Zinc, max %	0.001	0.001	0.001	0.002
Iron, max %	0.002	0.002	0.002	0.002
Bismuth, max %	0.050	0.005	0.025	0.150
Lead (by difference), min. %	99.94	99.90	99.90	99.85

[a]Corroding lead is a designation used in the trade for many years to describe lead refined to a high degree of purity.

Chemical lead is a term used in the trade to describe the undesilverized lead produced from Southeastern Missouri ores.

Acid-copper lead is made by adding copper to fully refined lead.

Common desilverized lead is a designation used to describe fully refined desilverized lead.

micrographs of lead fumes. The particles are nearly spherical and have a distinct tendency to agglomerate. The concentration of particulate matter in stack gases ranges from 1.4 to 4.5 grains per cubic foot.

Hooding and Ventilation Requirements

All the smoke and fumes produced by the reverberatory furnace must be collected and, since they are combined with the products of combustion, the entire volume emitted from the furnace must pass through the collector. It is not desirable to draw cool air into these furnaces through the charge doors, inspection ports, or other openings to keep air contaminants from escaping from them; therefore, external hoods are used to capture these emissions. The ventilating air for these hoods as well as for the hoods venting slag stations must also pass through the collector. In large furnaces, this represents a considerable volume of gases at fairly high temperatures.

Air Pollution Control Equipment

The only control systems found to operate satisfactorily in Los Angeles County have been those employing a baghouse as a final collector. These systems also include auxiliary items such as gas-cooling devices and settling chambers.

A pull-through type of baghouse with compartments that can be shut off one at a time is very satisfactory. This allows atmospheric air to enter one compartment and relieve any flow. The bags may then be cleaned by a standard mechanical shaking mechanism.

Provision should be made to prevent sparks and burning materials from contacting the filtercloth, and temperature must be controlled by preceding the baghouse with radiant cooling ducts, water-jacketed cooling ducts, or other suitable devices in order that the type of cloth used will have a reasonable life. The type of cloth selected depends upon parameters such as the temperature and corrosivity of the entering gases, and the permeability and abrasion- or stress-resisting characteristics of the cloth. Dacron bags are being successfully used in this service. The filtering velocity should not exceed 2 fpm. Test results of secondary lead-smelting furnaces venting to a baghouse control device are shown in Table 86.

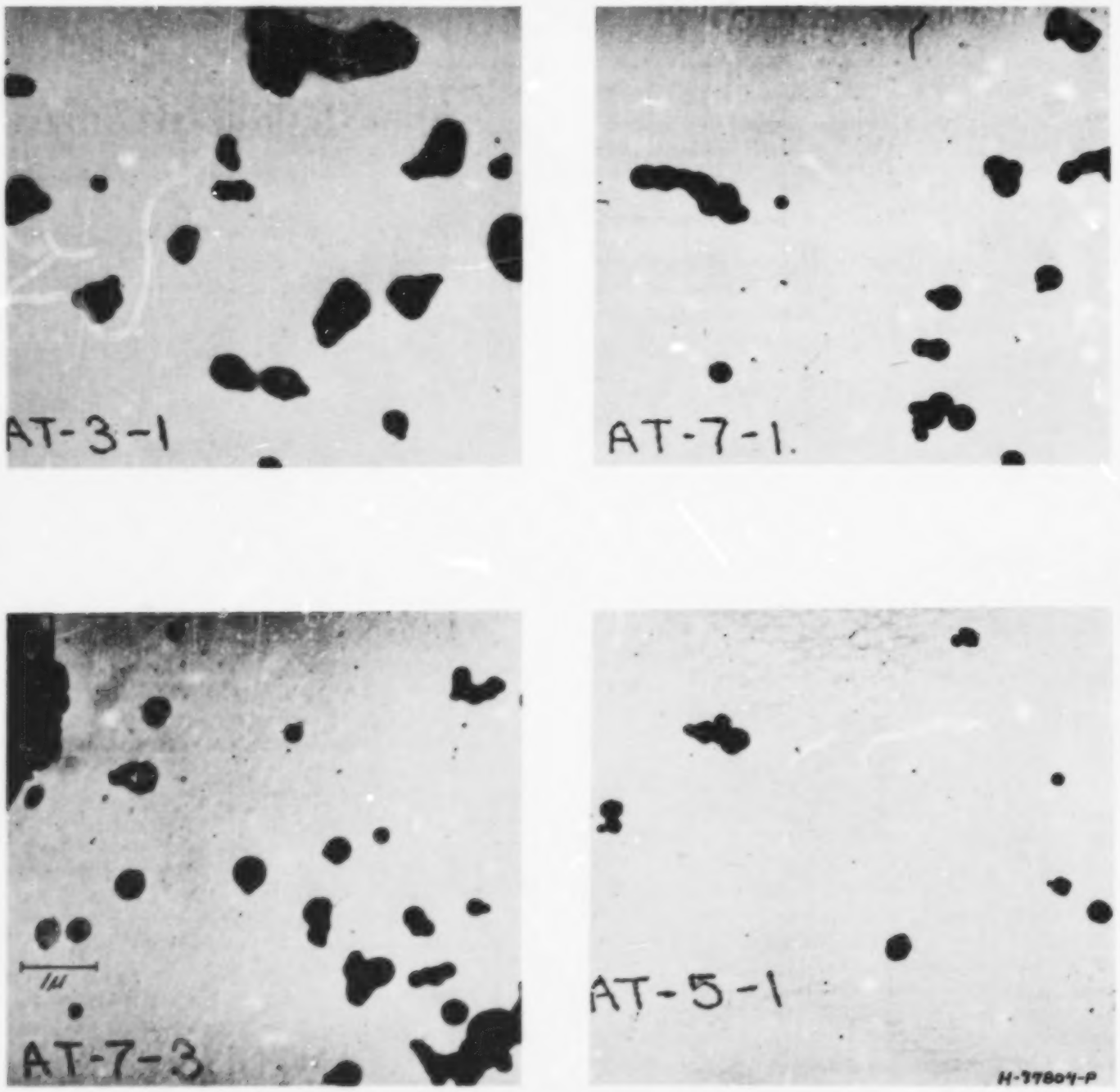


Figure 206. Electron photomicrographs of lead fumes (Allen et al., 1952).

The factors to be considered in designing these control systems are similar to those discussed previously in the sections on iron casting and steel manufacturing.

LEAD BLAST FURNACES

The lead blast furnace or cupola is constructed similarly to those used in the ferrous industry. The materials forming the usual charge for the blast furnace, and a typical percentage composition are 4.5 percent rerun slag, 4.5 percent scrap cast iron, 3 percent limestone, 5.5 percent coke, and 82.5 percent drosses, oxides, and reverberatory slags. The rerun slag is the highly silicated slag from previous blast furnace runs. The drosses are miscellaneous drosses consisting of copper drosses, caustic drosses, and dry drosses obtained from refining processes in the pot furnaces. The processes will be described in more detail in the following paragraphs. The coke is used as a source of heat, and combustion air is introduced near the bottom of the furnace through tuyeres at a gage pressure of about 8 to 12 ounces per square inch. Hard lead is charged into the cupola at the start of the operation to provide molten metal to fill the crucible. Normal

Table 86. DUST AND FUME EMISSIONS FROM A SECONDARY LEAD-SMELTING FURNACE

Test No.	1	2
Furnace data		
Type of furnace	Reverberatory	Blast
Fuel used	Natural gas	Coke
Material charged	Battery groups	Battery groups, dross, slag
Process weight, lb/hr	2,500	2,670
Control equipment data		
Type of control equipment	Sectioned tubular baghouse[a]	Sectioned tubular baghouse[a]
Filter material	Dacron	Dacron
Filter area, ft^2	16,000	16,000
Filter velocity, fpm at 327°F	0.98	0.98
Dust and fume data		
Gas flow rate, scfm		
Furnace outlet	3,060	2,170
Baghouse outlet	10,400[b]	13,000[b]
Gas temperature, °F		
Furnace outlet	951	500
Baghouse outlet	327	175
Concentration, gr/scf		
Furnace outlet	4.98	12.3
Baghouse outlet	0.013	0.035
Dust and fume emission, lb/hr		
Furnace outlet	130.5	229
Baghouse outlet	1.2	3.9
Baghouse efficiency, %	99.1	98.3
Baghouse catch, wt %		
Particle size 0 to 1 μ	13.3	13.3
1 to 2	45.2	45.2
2 to 3	19.1	19.1
3 to 4	14.0	14.0
4 to 16	8.4	8.4
Sulfur compounds as SO_2, vol %		
Baghouse outlet	0.104	0.03

[a]The same baghouse alternately serves the reverberatory furnace and the blast furnace.
[b]Dilution air admitted to cool gas stream.

charges, as outlined previously, are then added as the material melts down. The limestone and iron form the flux that floats on top of the molten lead and retards its oxidation.

As the level of molten material rises, the slag is tapped at intervals while the molten lead flows from the furnace at a more or less continuous rate. The lead product is "hard" or "antimonial." Approximately 70 percent of the molten material is tapped off as hard lead, and the remaining 30 percent, as slag. About 5 percent of the slag is retained for rerun later.

The Air Pollution Problem

Combustion air from the tuyeres passing vertically upward through the charge in a blast furnace conveys oxides, smoke, bits of coke fuel, and other particulates present in the charge. A typical material balance based upon the charge to a blast furnace in which battery groups are being processed is 70 percent recovery of lead, 8 percent slag, 10 percent mat (sulfur compounds formed with slag), 5 percent water (moisture contained in charge), and 7 percent dust (lead oxide and other particulates discharged from stack of furnace with gaseous products of combustion). Particulate matter loading in blast furnace gases is exceedingly heavy, up to 4 grains per cubic foot. The particle size distribution is very similar to that from gray iron cupolas, as described previously in the section on "Iron Casting."

Blast furnace stack gas temperatures range from 1,200° to 1,350°F. In addition to the particulate matter, which consists of smoke, oil vapor, fume, and dust, the blast furnace stack gases contain carbon monoxide. An afterburner is nec-

essary to control the gaseous, liquid, and solid combustible material in the effluent.

Hooding and Ventilation Requirements

The only practical way to capture the contaminants discharged from a lead blast furnace is to seal the furnace and vent all the gases to a control system. The hooding and ventilation requirements are very similar to those for the gray iron cupola, which are discussed in the section on "Iron Casting."

Air Pollution Control Equipment

The control system for a lead blast furnace is similar to that employed for gray iron cupola furnaces except that electrical precipitators are not used for economic reasons. Moreover, difficulties are encountered in conditioning the particles to give them resistivity characteristics in the range that will allow efficient collection.

The factors to be considered in designing a control system for a blast furnace, including an afterburner and a baghouse, have been discussed in the section on "Iron Casting."

POT-TYPE FURNACES

Pot-type furnaces are used for remelting, alloying, and refining processes. Remelting is usually done in small pot furnaces, and the materials charged are usually alloys in the ingot form, which do not require any further processing except to be melted for casting operations.

The pots used in the secondary smelters range from the smallest practical size of 1-ton capacity up to 50 tons. Figure 207 is a photograph of two pot furnaces utilizing a common ventilation hood. These furnaces are usually gas fired. Various refining and alloying operations are carried on in these pots. Alloying usually begins with a metal lower in the percentage of alloying materials than desired. The percent desired is calculated and the amount is then added. Antimony, tin, arsenic, copper, and nickel are the most common alloying elements used.

The refining processes most commonly employed are those for the removal of copper and antimony to produce soft lead, and those for the removal of arsenic, copper, and nickel to produce hard lead. For copper removal, the temperature of the molten lead is allowed to drop to 620°F and sulfur is added. The mixture is agitated and copper sulfide is skimmed off as dross. This is known as "copper dross" and is charged into the blast furnace.

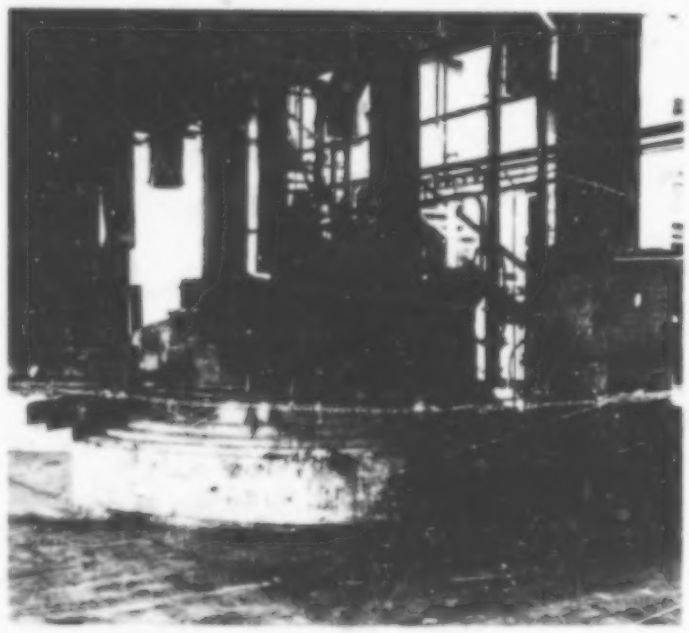


Figure 207. An installation used to capture emissions from two lead pot furnaces. Hood serves either furnace alternately (Morris P. Kirk & Son, Inc., Los Angeles, Calif.).

When aluminum is added to molten lead, it reacts preferentially with copper, antimony, and nickel to form complex compounds that can be skimmed from the surface of the metal. The antimony content can also be reduced to about 0.02 percent by bubbling air through the molten lead. It can be further reduced by adding a mixture of sodium nitrate and sodium hydroxide and skimming the resulting dross from the surface of the metal.

Another common refining procedure, "dry drossing," consists of introducing sawdust into the agitated mass of molten metal. This forms carbon, which aids in separating the globules of lead suspended in the dross, and reduces some of the lead oxide to elemental lead.

In areas where there is no great concern about air pollution, a mixture of sal ammoniac and rosin may be used to clean the metal of impurities. This method, however, produces copious quantities of dense, white fumes, and obnoxious odors. In areas having air pollution laws, this method is generally no longer used.

The Air Pollution Problem

Although the quantity of air contaminants discharged from pot furnaces as a result of remelting, alloying, and refining is much less than that from reverberatory or blast furnaces, the capture and control of these contaminants is equally important in order to prevent periodic violations

of air pollution regulations and protect the health of the employees.

Problems of industrial hygiene are inherent in this industry. People working with this equipment frequently inhale and ingest lead oxide fumes, which are cumulative, systemic poisons. Frequent medical examinations are necessary for all employees, and a mandatory dosage of calcium disodium versenate may be required daily in order to keep the harmful effects to a minimum.

Hooding and Ventilation Requirements

Hood design procedures for pot furnaces are the same as those outlined for electric-induction furnaces mentioned earlier in this chapter.

Air Pollution Control Equipment

The control systems for pot furnaces, as with the other lead furnaces, require the use of a baghouse for the final collector. The temperature of the gases is, however, generally much lower than that from the other furnaces; therefore, the gas-cooling devices, if needed, will be much smaller. Afterburners are generally not required.

BARTON PROCESS

A rather specialized phase of the industry is the production of lead oxide. Battery lead oxide, containing about 20 percent finely divided free lead, is usually produced by the Barton process. Molten lead is run by gravity from a melting pot into a kettle equipped with paddles. The paddles are rotated at about 150 rpm, rapidly agitating the molten lead, which is at a temperature of 700° to 900°F. Air is drawn through the kettles by fans located on the air outlet side of a baghouse. The lead oxide thus formed is conveyed pneumatically to the baghouse where it is collected and delivered by screw conveyor to storage.

Other lead oxides requiring additional processing but commonly made are red lead oxide (minium, Pb_3O_4), used in the paint industry, and yellow lead oxide (litharage or massicot, PbO), used in the paint and ink industries.

Since the process requires the use of a baghouse to collect the product, and no other contaminants are discharged, no air pollution control system as such is needed.

METAL SEPARATION PROCESSES

In addition to the metallurgical processes previously mentioned in this chapter, there are other processes classified as metal separation that can be troublesome from an air pollution standpoint. In these, the metal desired is recovered from scrap, usually a mixture of several metals. Probably the most common of these processes, aluminum sweating, is the recovery of aluminum from aluminum drosses and other scrap. Other examples of metal separation processes include the recovery processes for zinc, lead, solder, tin, and low-melting alloys from a host of scrap materials.

ALUMINUM SWEATING

Open-flame, reverberatory-type furnaces are used by secondary smelters to produce aluminum pigs for remelting. These furnaces are constructed with the hearths sloping downward toward the rear of the furnace. All types of scrap aluminum are charged into one of these furnaces, which operates at temperatures of 1,250° to 1,400°F. In this temperature range, the aluminum melts, trickles down the hearth, and flows from the furnace into a mold. The higher melting materials such as iron, brass, and dross oxidation products formed during melting remain within the furnace. This residual material is periodically raked from the furnace hearth.

Some large secondary aluminum smelters separate the aluminum suspended in the dross by processing the hot dross immediately after its removal from the metal in the refining furnace. The hot dross is raked into a refractory-lined barrel to which a salt-cryolite flux is added. The barrel is placed on a cradle and mechanically rotated for several minutes. Periodically, the barrel is stopped and the metal is tapped by removing a clay plug in the base of the barrel. This process continues until essentially all the free aluminum has been drained and only dry dross remains. The dross is then dumped and removed from the premises. A hot dross-processing station has been illustrated previously in Figure 200.

The aluminum globules suspended in the dross as obtained from the hot dross process can also be separated and reclaimed by a cold, dry, milling process. In this process the large chunks of dross are reduced in size by crushing and then fed continuously to a ball mill where the oxides and other nonmetallics are ground to a fine powder, which allows separation from the larger solid particles of aluminum. At the mill discharge, the fine oxides are removed pneumatically and conveyed to a baghouse for ultimate disposal. The remaining material passes over a magnetic roll to remove tramp iron and is then discharged into storage bins to await melting. This process is used primarily to process drosses having a low aluminum content.

ZINC, LEAD, TIN, SOLDER, AND LOW-MELTING ALLOY SWEATING

Although recovery of aluminum is the most common of the metal separation processes, others that contribute to air pollution deserve mention. These include zinc, lead, tin, solder, and low-melting alloy sweating. Separation of these metals by sweating is made possible by the differences in their melting point temperatures. Some of these melting temperatures are:

Tin	450°F
Lead	621°F
Zinc	787°F
Aluminum	1,220°F
Copper	1,981°F
Iron	2,795°F

When the material charged to a sweating furnace contains a combination of two of these metals, it can be separated by carefully controlling the furnace temperature so that the metal with the lower melting point is sweated when the furnace temperature is maintained slightly above its melting point. After this metal has been melted and removed, the furnace burners are extinguished and the metal with the higher melting point is raked from the hearth.

Zinc can be recovered by sweating in a rotary, reverberatory, or muffle furnace. Zinc-bearing materials fed to a sweating furnace usually consist of scrap die-cast products such as automobile grilles, license plate frames, and zinc skims and drosses.

The sweating of lead from scrap and dross is widely practiced. Junk automobile storage batteries supply most of the lead. In addition, lead-sheathed cable and wire, aircraft tooling dies, type metal drosses, and lead dross and skims are also sweated. The rotary furnace, or sweating tube, is usually used when the material processed has a low percent of metal to be recovered. The reverberatory box-type furnace is usually used when the percent of metal recovered is high.

Rotary and reverberatory furnaces are also used to sweat solder and other low-melting alloys from scrap metal. Automobile radiators and other soldered articles such as gas meter boxes, radio chassis, and so forth, make up the bulk of the process metal. For this recovery, the furnace is usually maintained between 650°F and 700°F. Higher temperatures should be avoided in order to prevent the possible loss of other recoverable metals. For example, sweating automobile radiators at 900°F causes excessive oxidation of the copper.

The Air Pollution Problem

Contaminants From Aluminum-Separating Processes

In theory, an aluminum-sweating furnace can be operated with minor emissions of air contaminants if clean, carefully hand-picked metal free of organic material is processed. In practice, this selective operation does not occur and excessive emissions periodically result from uncontrolled furnaces. Stray magnesium pieces scattered throughout the aluminum scrap are not readily identified, and charging a small amount of magnesium into a sweating furnace causes large quantities of fumes to be emitted. Emissions also result from the other materials charged, such as skims, drosses, scrap aluminum sheet, pots and pans, aircraft engines, and wrecked airplanes containing oil, insulated wire, seats, instruments, plastic assemblies, magnesium and zinc components, and so forth.

Smoke is caused by the incomplete combustion of the organic constituents of rubber, oil and grease, plastics, paint, cardboard, and paper. Fumes result from the oxidation of stray magnesium or zinc assemblies and from the volatilization of fluxes in the dross. The sweating of dross and skims is responsible for the high rates of emission of dust and fumes. Residual aluminum chloride flux in the dross is especially troublesome because it sublimes at 352°F and is very hygroscopic. In addition, it hydrolyzes and forms very corrosive hydrogen chloride. In Table 87, test 1 shows results from an aluminum-sweating furnace.

In the dry milling process, dust is generated at the crusher, in the mill, at the shaker screens, and at points of transfer. These locations must be hooded to prevent the escape of fine dust to the atmosphere.

When aluminum is reclaimed by the hot dross process, some fumes are emitted from the flux action; however, the main air pollution problem is the collection of the mechanically generated dust created by the rotation of the dross barrel.

Contaminants from low-temperature sweating

Air contaminants released from a zinc-sweating furnace consist mainly of smoke and fumes. The smoke is generated by the incomplete combustion of the grease, rubber, plastics, and so forth contained in the material. Zinc fumes are negligible at low furnace temperatures, for they have a low vapor pressure even at 900°F. With elevated furnace temperatures, however, heavy fuming can result. In Table 87, test 2 shows results from a zinc die-cast-sweating operation.

Table 87. DUST AND FUME EMISSIONS FROM AN ALUMINUM- AND A ZINC-SWEATING FURNACE CONTROLLED BY A BAGHOUSE

Test No.	1	2
Furnace data		
Type of furnace	Reverberatory	Reverberatory
Size of furnace	5 ft 9 in. W x 6 ft 4 in. L x 4 ft H	5 ft 9 in. W x 6 ft 4 in. L x 4 ft H
Process weight, lb/hr	760	2,080
Material sweated	Aluminum skims	Zinc castings
Baghouse data		
Type of baghouse	Sectioned tubular	Sectioned tubular
Filter material	Orlon	Orlon
Filter area, ft^2	5,184	5,184
Filter velocity, fpm	1.9	1.85
Precleaner	None	None
Dust and fume data		
Gas flow rate, scfm		
Baghouse inlet	8,620	7,680
Baghouse outlet	9,580	7,420
Average gas temperature, F		
Baghouse inlet	137	190
Baghouse outlet	104	173
Concentration, gr/scf		
Baghouse inlet	0.124	0.205
Baghouse outlet	0.0138	0.0078
Dust and fume emission, lb/hr		
Baghouse inlet	9.16	13.5
Baghouse outlet	1.13[a]	0.5
Control efficiency, %	87.7[a]	96.3

[a] Visible emissions released from the baghouse indicated that a bag had broken during the latter part of the test.

The discharge from a lead-sweating furnace may be heavy with dust, fumes, smoke, sulfur compounds, and fly ash. This is particularly true when junk batteries are sweated. The battery groups and plates removed from the cases contain bits of asphaltic case, oil and grease around the terminals, sulfuric acid, lead sulfate, lead oxide, and wooden or glass fiber plate separators. The organic contaminants burn poorly and the sulfur compounds release SO_2 and SO_3. The sulfur trioxide is particularly troublesome; when hydrolized to sulfuric acid, the acid mist is difficult to collect and is extremely corrosive. The lead oxide tumbles within the rotating furnace and the finer material is entrained in the vented combustion gases.

Unagglomerated lead oxide fume particles vary in diameter from about 0.07 to 0.4 micron, with a mean of about 0.3 micron (Allen et al., 1952). Uncontrolled rotary lead sweat furnaces emit excessively high quantities of air contaminants. Although the other types of scrap lead and drosses sweated in a reverberatory furnace are normally much less contaminated with organic matter and acid, high emission rates occur periodically.

The contaminants generated during the sweating of solder, tin, and other low-melting alloys consist almost entirely of smoke and partially oxidized organic material. The scrap metal charged is usually contaminated with paint, oil, grease, rust, and scale. Automobile radiators frequently contain residual antifreeze and sealing compounds.

Hooding and Ventilation Requirements

The ventilation and hooding of reverberatory furnaces and rotary furnaces used for the reclamation processes just mentioned are similar to those of furnaces of this type previously discussed in this chapter. The exhaust system must have sufficient capacity to remove the products of combustion at the maximum firing rate and provide adequate collection of the emissions from any furnace opening.

In aluminum separation operations, raking the residual metal and dross from the furnace is a critical operation from an air pollution standpoint, and hoods should be installed to capture emis-

sions at these locations. The required exhaust volume may be effectively reduced by providing a guillotine-type furnace door and opening it only as needed to accomplish charging and raking. If the burners are turned off during these operations, the indraft velocity through the charging and raking opening is effectively increased and the emissions from this location are reduced.

In low-temperature sweating operations, auxiliary hooding is usually necessary and varies with the type of sweating furnace. For the conventional reverberatory-type furnace, a hood should be installed above the furnace door so that escaping fumes can be captured. The emissions occur both during the normal melting process and during the raking of the residual material from the hearth. A rotary sweating furnace usually needs only a hood over the high end of the tube. In cases where the drosses are fine and dusty, however, a hood is necessary at the discharge end, too. If the hoods are well designed and no unusual crossdrafts are present, an indraft velocity of 100 to 200 fpm is adequate to prevent the escape of the air contaminants.

Air Pollution Control Equipment

Aluminum-separating processes

Although air pollution control equipment is necessary in aluminum reclamation processes, some operating procedures reduce the quantity of emissions. Whenever possible the stray magnesium pieces and combustible material should be removed from the aluminum scrap to be sweated. The furnace burners should be operated so that the flame does not impinge on the scrap metal, particularly if the burners are oil fired.

An afterburner followed by a baghouse is recommended as control equipment for an aluminum-sweating furnace. Baghouse filtering velocities should not exceed 3 fpm. The afterburner must be so designed that the carbonaceous material is intimately mixed with the exhaust air and held at a suitable temperature for a sufficient length of time to ensure complete incineration. For this service, an afterburner temperature of 1,200° to 1,400°F is recommended with a retention time of the gases in this hot zone of about 0.3 second. A luminous-flame afterburner is generally the most desirable because of the greater flame area. Secondary air may have to be admitted to the afterburner to ensure complete combustion. The afterburner may be constructed as a separate unit from the furnace or may be constructed as an integral part of the furnace somewhat similar to a multiple-chamber incinerator. General design features of afterburners have been discussed in Chapter 5.

The hot gases must be cooled before entering a baghouse, and radiant cooling or dilution with cold air is recommended in preference to evaporative cooling with water. The sweating of aluminum drosses may result in severe corrosion problems owing to the aluminum chloride flux contained in the dross. If the hot furnace gases are cooled with water before entering the baghouse, the aluminum chloride hydrolyzes, producing hydrochloric acid. The ductwork and bags are attacked, rapidly impairing the collection efficiency of the filter. Even the condensation from night air during shutdowns provides sufficient moisture to corrode the equipment in the presence of these chemicals.

Figure 208 shows an aluminum sweating furnace with integral afterburner venting through horizontally positioned radiation-convection cooling columns to a settling chamber and baghouse. The furnace charging door hood is vented directly to the baghouse. Table 88 shows test data acquired while aluminum scrap heavily contaminated with combustible material was being sweated in the furnace. Combustible carbon was present in the particulate discharge and was coexistent in the vent stream with excess oxygen as shown by the Orsat analysis. This indicates that the rate of combustible discharge from the scrap aluminum was in excess of the incinerating capacity of the afterburner.

In the hot-dross process, the rotating barrel need only be properly hooded and ducted to a baghouse. No afterburning is required, and because of the relatively large indraft air volume, no gas-cooling facilities are required in the exhaust system.

In the dry milling process, the ball mill, crusher, and all transfer points must be hooded and vented to a baghouse in order to prevent the escape of the dust created. The required hood indraft velocities vary from 150 to 500 fpm, depending upon crossdrafts and the force with which the dust is generated. A baghouse filter velocity of 3 fpm or less is recommended. No afterburning or gas-cooling facilities are required in a dry-dross control system.

Low-temperature sweating

An afterburner should be provided to incinerate the combustible matter discharged from a low-temperature sweating furnace.

Since an afterburner cannot remove the noncombustible portion of the effluent, a baghouse should be used with the afterburner to capture the dust and fumes. The maximum recommended baghouse filter velocity is 3 fpm. In certain special applications where the only emissions are oils or other combustible material, an afterburner

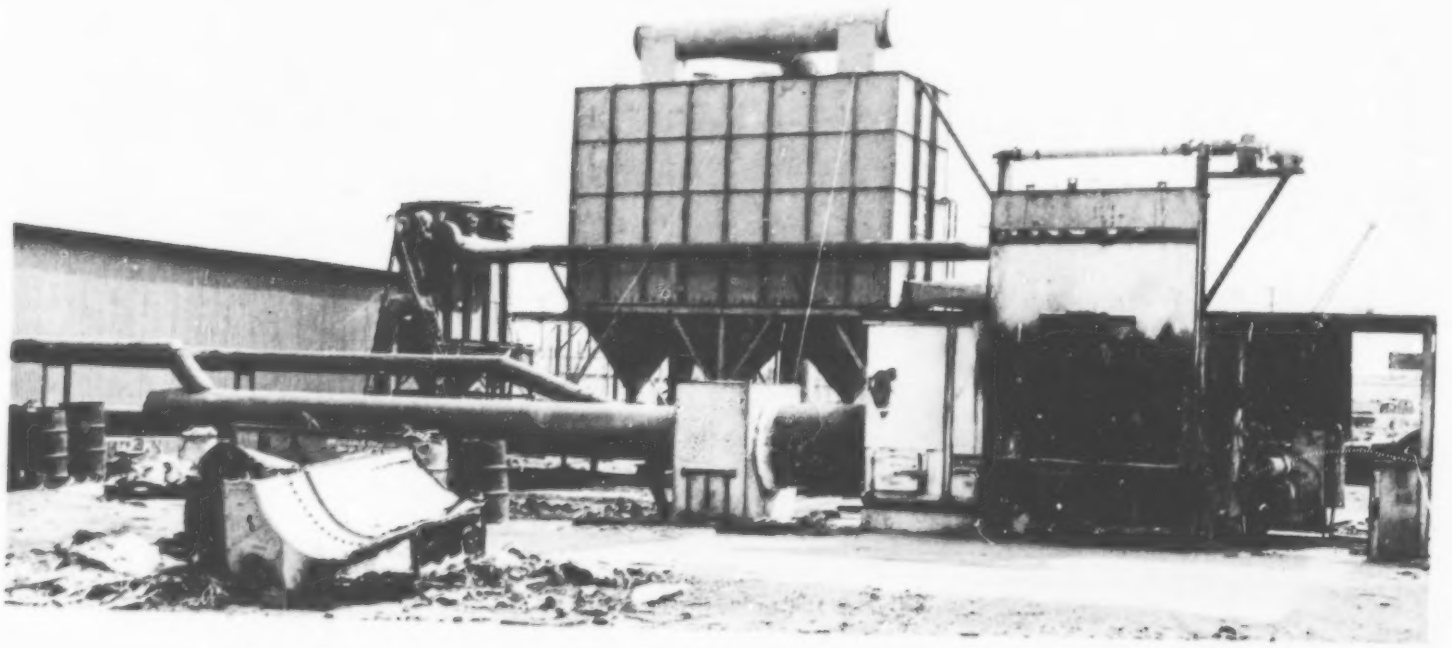


Figure 208. Aluminum-sweating furnace vented to an afterburner and baghouse (Du-Pol Enterprises, Los Angeles, Calif.).

can be used to incinerate the contaminant, and a baghouse may not be required. Conversely, only a baghouse is required when the process scrap is always free of oils or other combustible waste. Water scrubbers have not proved satisfactory in the collection of metallic fumes of this type.

CORE OVENS

In foundries, core ovens are used to bake the cores used in sand molds. Most cores contain binders that require baking to develop the strength needed to resist erosion and deformation by metal during the filling of the mold. Core ovens supply the heat and, where necessary, the oxygen necessary for the baking. Cores are made in a large variety of sizes and shapes and with a variety of binders; therefore, a variety of types of core ovens are needed to provide the space and heat requirements for baking the cores.

Generally, emissions from core ovens are a minor source of air pollution when compared with other metallurgical processes. If the ovens are operated below 400°F and are fired with natural gas, emissions are usually tolerable. Nevertheless, there are instances, for example, when special core formulations are used, when emissions can have opacities exceeding legal limits permitted in Los Angeles County, and when emissions can be extremely irritating to the eye because of aldehydes and other oxidation products. In these cases, a control device is necessary, normally an afterburner.

TYPES OF OVENS

The various types of core ovens fall into the following five classes: Shelf ovens, drawer ovens, portable-rack ovens, car ovens, conveyor ovens.

Shelf ovens are probably the simplest form of core ovens. They are merely insulated steel boxes, divided into sections by shelves. Core plates carrying cores are placed directly on the shelves. When a door is opened, all or at least several shelves are exposed and a large amount of heat escapes from the oven chamber. Figure 209 shows a gas-fired shelf oven. The hot gases escaping during loading and unloading of the sheives not only waste heat but also create undesirable working conditions. Because of these undesirable characteristics, these ovens are generally limited to baking small cores, particularly in a small-core department where the investment in oven equipment must be kept at a minimum.

Shelf ovens have been replaced largely by the more efficient drawer oven. One type of drawer oven is shown in Figure 210. With these ovens, one or more drawers can be withdrawn for loading or unloading and, since the drawers are equipped with rear-closing plates, hot gases do not escape. Within the oven, the drawers are supported on rollers and, when withdrawn, the front end is supported by an overhead drawer-selector with an operating arrangement to permit engagement of any one or any combination of drawers.

Table 88. DUST AND FUME EMISSIONS FROM AN ALUMINUM-SWEATING FURNACE CONTROLLED BY AN AFTERBURNER AND BAGHOUSE

Furnace data			
Type of furnace	Reverberatory with integral afterburner		
Furnace hearth area	4 ft 7 in. W x 8 ft 10 in. L		
Process weight, lb/hr	2,870		
Material sweated	Scrap aluminum		
Baghouse data			
Type of bags	Tubular		
Filter material	Dacron		
Filter area, ft^2	4,800		
Filter velocity, fpm	2.16		
Precleaner	Settling chamber		
Dust and fume data	Settling chamber inlet	Furnace charge door hood	Baghouse outlet
Gas flow rate, scfm	1,360	5,580	8,850[a]
Average gas temperature, °F	350	204	150
Concentration, gr/scf	0.505	0.081	0.0077
Dust and fume emission, lb/hr	5.89	3.88	0.58
Particulate control efficiency, %			94.1
Orsat analysis at settling chamber inlet, volume %			
CO_2	6.8		
O_2	8.6		
CO	0.02		
N_2	77.33		
H_2O	7.25		
Particle size analysis at baghouse outlet, wt %			
+60 mesh	85.9		
-60 mesh	14.1		
Particle size analysis of -60 mesh portion, wt %			
0 to 2 μ	6.9		
2 to 5 μ	32.4		
5 to 10 μ	30.9		
10 to 20 μ	17.7		
20 to 40 μ	7.7		
< 40 μ	4.4		
Combustible carbon in particulate discharge, dry wt %			
Settling chamber inlet	83.7		
Furnace chamber door hood exit	67.3		

[a]Volume is greater at the baghouse exit than at the inlet because of leakage.

These ovens are suitable for baking small- and medium-sized cores, but they are limited in the volume of cores that can be baked because of labor involved in transporting the cores from the core maker to the oven, placing them in the drawers, removing them from the drawers, and taking them to storage.

To overcome some of the handling of cores, portable rack ovens were developed. The core maker places his cores directly onto a rack, which, when filled, is put into the oven. After the baking, the rack is removed and taken to storage. A different, loaded rack can then be placed in the oven. Figure 211 shows an empty rack oven.

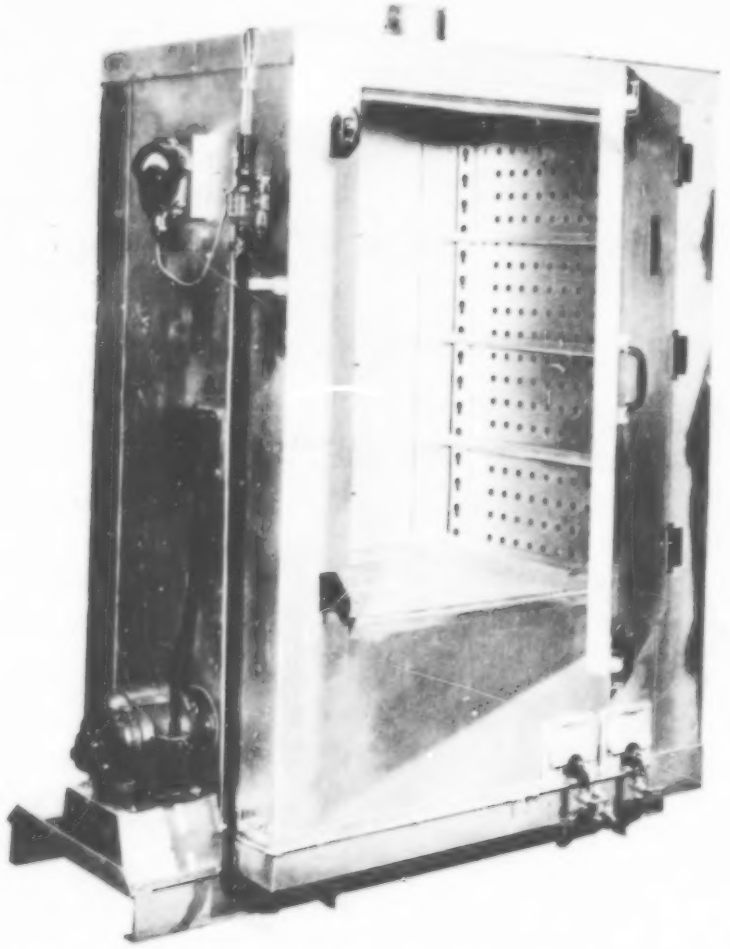


Figure 209. Shelf oven (The Foundry Equipment Co., Cleveland, Ohio).

Racks are designed not only to fit the oven but also to accommodate large or small cores. They can be transported by an overhead monorail or lift trucks, either manually or power operated.

For large cores, car ovens are generally used. These ovens are similar to rack ovens but larger and, instead of portable racks, cars riding on rails are used. The cores, being large and heavy, are generally loaded on the cars by crane. Tiered pallets are frequently used to facilitate car loading. Because of the size of the cores, most of a day is usually needed to load a car; therefore, baking is usually done overnight.

Conveyor ovens are used in foundries where a large volume of cores of approximately the same size are baked. Of course, larger cores can also be baked by allowing them to make two or more passes through the oven.

Conveyor ovens have loading and unloading stations, a heated section, and a cooling section. A horizontal-conveyor oven is shown in Figure 212. These ovens are generally located above the floor level, in roof trusses, or above areaways between buildings. They have inclined entrances and exits to allow loading at the floor level and, probably more important, to provide natural-draft heat seals. The vertical-conveyor oven shown in Figure 213 requires little floor space for a large volume of baking. It is heated on the

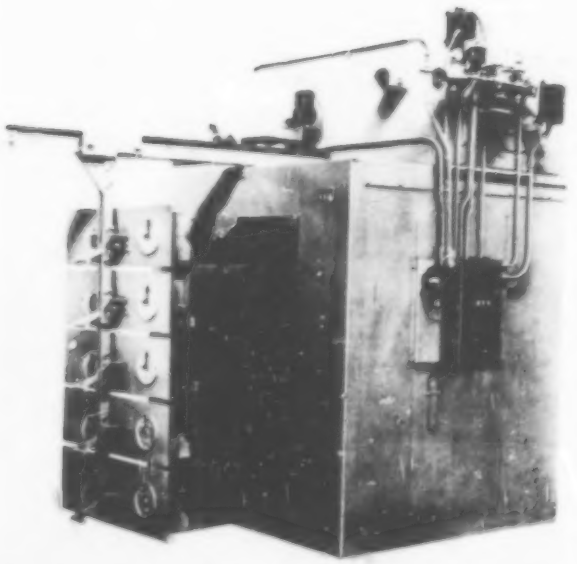


Figure 210. Drawer oven (Despatch Oven Co., Minneapolis, Minn.).

Figure 211. Rack oven (Despatch Oven Co., Minneapolis, Minn.).

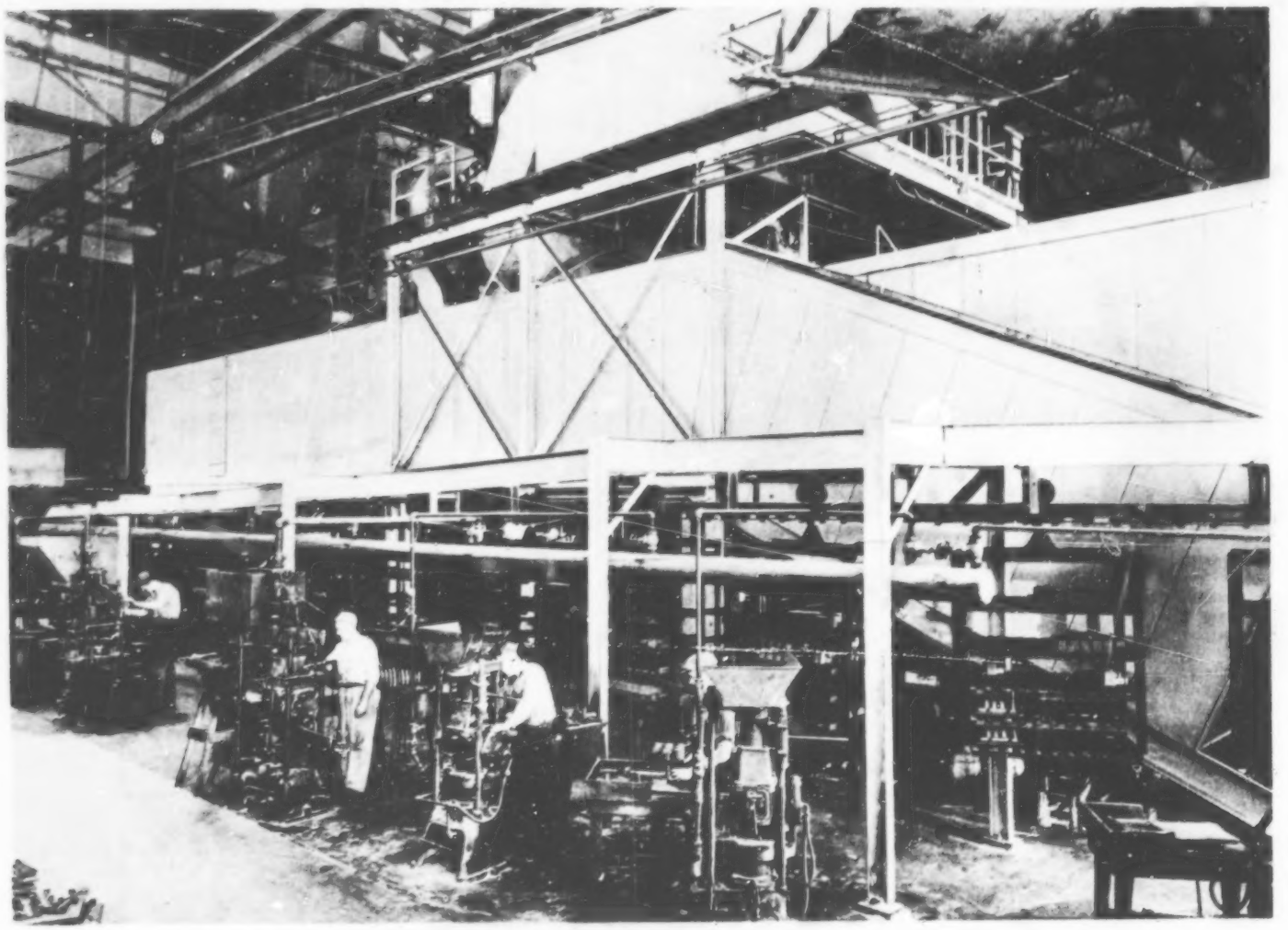


Figure 212. Horizontal, continuous oven (The Foundry Equipment Co., Cleveland, Ohio).

side where the cores enter the oven and throughout the top of the oven. With the use of baffles and a blower, the lower portion of the unloading side of the oven cools the baked cores. Core makers can be grouped around the loading side of the oven to minimize the handling of cores.

HEATING CORE OVENS

Probably the simplest and crudest method of heating core ovens is to use burners along the floor extending the entire length of the oven. These burners cannot be regulated automatically and they do not provide uniform heat throughout the oven. They can be dangerous, because of damping out of the flame at the back of an oven, which allows raw gas to accumulate resulting in explosions. Although a few ovens are still heated in this manner, most ovens use recirculating heater units.

With recirculating heaters, a portion of the oven gases is returned to the heater, and the rest is vented through a dampered stack to the atmosphere. Fresh air is mixed with the recirculated gases, and the mixture is heated. The hot gases and the products of combustion are blown into the oven. The amount of fresh air admitted is controlled by the amount of gases vented from the oven and only enough is admitted to supply the oxygen needed for the baking process.

CORE BINDERS

The primary reason for baking cores is to make them strong enough so that they can be handled while the mold is being made and so that they resist erosion and deformation by metal when the mold is being filled. The baking process drives off water and other volatiles, which reduces the total gas-forming material in the mold. Most of the "volatiles" discharged can be considered air contaminants. Their composition depends upon the type of binder used in the core.

Numerous binders require baking, but they do not all harden by the same chemical and physical processes. Based on their method of hardening,

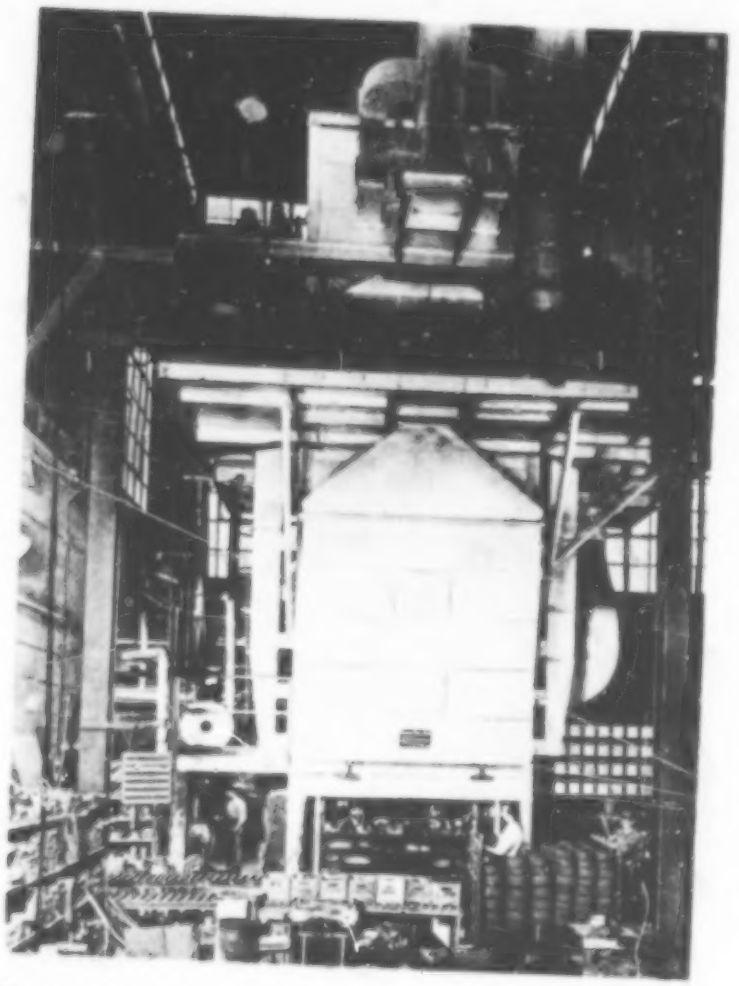


Figure 213. Vertical, continuous oven (The Foundry Equipment Co., Cleveland, Ohio).

the binders can be subdivided into three types: (1) Those that harden upon heating, (2) those that harden upon cooling after being heated, and (3) those that adhere upon heating. The binders of the first type develop their strength by chemical reaction, while those of the second and third types function through physical phenomena.

Pitch, rosin, and similar materials of type 2 are solids at room temperature, but upon heating, they melt and flow around the sand grains. When the mixture of sand and binder cools, the binder solidifies and holds the grains together. Those binders are frequently dissolved or dispersed in solvent and, when baked, the solvent is driven off, becoming an air contaminant.

The binders of type 3 are mixed with sand in the dry state. Water is then added and the binder becomes gelatinous, which imparts green strength to the mixture. Upon baking, these binders dehydrate, harden, and adhere to the sand grains holding them together. Since baking only drives water from the mixture, no air contaminants are created.

Type-1 binders harden by chemical action, partial oxidation, and polymerization. Drying oils, of which linseed oil is typical, are made up of unsaturated hydrocarbons that are liquid at room temperature. Because they are unsaturated, the molecules can react with other molecules or elements without producing side products. These oils react with oxygen very slowly at room temperature and faster at elevated temperatures, to the extent that their unsaturation is partially satisfied, and then they polymerize to form a solid film that holds the sand grains together. If, however, too much heat is applied, the oxidation process goes too far and some molecules break up into lower molecular weight products instead of polymerizing. The result is a weaker film, and smoke, vapors, and gases are discharged.

The resin-type binders, such as phenol-formaldehyde, are intermediate, easily polymerized products of a phenol and formaldehyde condensation reaction. When heated, these compounds polymerize rapidly into a hard film. No side reactions should, however, occur; these substances, too, are organic and subject to burning if heated excessively.

In actual practice, cores seldom contain only one type of binder. A typical core mixture contains 930 pounds of sand, 7-1/2 pounds of core oil, 9 pounds of cereal binder, 3 pounds of kerosene, and 38 pounds of water. The core oil contains 45 percent linseed oil, 28 percent gum rosin, and 27 percent kerosene. All three types of binder are present. The linseed oil in the core oil is a type-1 binder and hardens by an oxidation-polymerization process. The gum rosin of the core oil is a type-2 binder and, after its solvents are driven off, it melts and then hardens when the cores are cooled. The cereal binder is corn flour, a type-3 binder, which is used to impart green strength to the core by its gelatinous reaction with water before the core is baked.

During the baking of these cores, a series of physical and chemical reactions occurs. First, the moisture and light fractions of the oil are distilled off. As the temperature rises, the heavier fractions of the kerosene are vaporized and the linseed oil begins to react with oxygen and to polymerize. At about 300°F, the rosin melts, coating the grains with a thin film of rosin.

The polymerization of the linseed oil requires more time than the physical changes that take place do, and so the core is held at a temperature of 375°F for 1-1/2 to 3-1/2 hours to develop maximum strength. A higher temperature accelerates the polymerization, but the danger of overbaking is also much greater. For instance, when linseed oil is baked at 375°F, its maximum strength is achieved in 1-1/2 hours, and its

strength does not deteriorate if it is baked for 3-1/2 hours. At 400°F, a maximum strength, less than that achieved at 375°F, is reached in 3/4 hour, but the strength begins to deteriorate if the core is baked longer than 1-1/4 hours. And at 450°F, the maximum strength is reached in a little less than 3/4 hour and immediately begins to deteriorate if overbaked. Of course, since the entire body of the core cannot reach the oven temperature at the same time, if high temperatures are used the surface of the core is overbaked before the inner portions are completely baked. Moreover, the high temperatures tend to create smoke and objectionable gases that are discharged from the oven as air contaminants.

The resinous-type binders also have kerosene and cornflour added. Baking time and temperature requirements are, however, much less. In fact, high-frequency dielectric ovens can be used with the fast-setting synthetic resins. In these ovens, the electrical field created causes nonconductors within the field to become hot. The ovens generally have a relatively small heating space, through which a conveyor carries the cores. The conveyor is one of the electrodes; therefore, only the cores become heated. There are no hot gases to contend with, and only the small amount of volatile materials in the cores are discharged. Baking time generally runs 2-1/2 minutes.

The Air Pollution Problem

The air contaminants discharged from core ovens consist of organic acids, aldehydes, hydrocarbon vapors, and smoke. The vapors are the result of the evaporation of hydrocarbon solvents, usually kerosene, and the light ends usually present in core oils. The organic acids, aldehydes, and smoke are the result of partial oxidation of the various organic materials in the cores. These substances have obnoxious odors and are very irritating to the eyes. The quantity and irritating quality of the oxidation products generally increase with an increase in baking temperature.

Emission rates, in general, are low, especially from small- and medium-sized ovens operating at 400°F or less. With some core binders, however, the emissions from small ovens operating at low temperatures can be of sufficient quantity to create a public nuisance. The emissions from larger ovens are generally greater and are more apt to create nuisances or be in excess of opacity regulations. Table 89 shows the amounts of various contaminants discharged from three core ovens. Test 1 shows the emissions from an uncontrolled oven, and tests 2 and 3 show the emissions from two ovens as well as the afterburners that control the emissions from them.

Table 89. AIR CONTAMINANT EMISSIONS FROM CORE OVENS

Test No.	1	2		3	
Oven data					
Size	6 ft 2 in. W x 7 ft 11 in. H x 19 ft L	3 ft 10 in. W x 5 ft 3 in H x 18 ft L		4 ft 2 in. W x 6 ft 8 in. H x 5 ft 9 in. L	
Type	Direct gas-fired	Direct gas-fired		Indirect electric	
Operating temp, °F	380	400		400	
Core binders	1 to 1/2% phenolic resin	3% linseed oil		1% linseed oil	
Weight of cores baked, lb	700	1,600		600	
Baking time, hr	11	2-1/2 to 3		6	
Afterburner data					
Size	None	10 in. dia x 7 ft 6 in. H		3 ft dia x 4 ft H	
Type		Direct flame		Direct flame	
Burner capacity, Btu/hr		200,000		600,000	
Air contaminants from:	Oven	Oven	Afterburner	Oven	Afterburner
Effluent gas volume, scfm	100	140	260	250	440
Effluent gas temperature, °F	380	400	1,400	400	1,780
Particulate matter, lb/hr	0.13	0.2	0.013	0.27	0.02
Organic acids, lb/hr	0.068	0.008	0.000	0.44	0.087
Aldehydes, ppm	52	10	10	377	4
Hydrocarbons, ppm	124	-	< 10	158	< 19
Opacity, %	0	-	0	-	0
Color	Slight	-	Slight	-	None

Excessive amounts of emissions can generally be expected from ovens operated at 500°F or higher, and from ovens in which the cores baked contain larger than normal amounts of kerosene, fuel oil, or core oils. Visible emissions are usually discharged from large conveyorized ovens. In many cases the opacity of these plumes has been in excess of Los Angeles County's opacity regulations.

Hooding and Ventilation Requirements

Most core ovens are vented directly to the atmosphere through a stack. The ovens require sufficient fresh air to be mixed with recirculated gases and with the products of combustion from the heater to keep the moisture content low and to supply the oxygen necessary for proper baking of the drying oil-type core binders.

Generally, the excess gases and any contaminants created are discharged from the oven through one vent stack. Occasionally more than one vent is used, but if the emissions are such that air pollution controls are needed, then ducting the vents to a control device is all that is necessary. The use of hoods or of excess air is not necessary to capture the emissions.

Air Pollution Control Equipment

As emphasized previously, when operated below 400°F and when fired with natural gas, most core ovens do not require air pollution control equipment. There have been, however, several cases where excessive emissions have been discharged and control equipment has been necessary.

Excessive emissions from core ovens have been reduced to tolerable amounts by modifying the composition of the core binders and lowering the baking temperatures. For instance, smoke of excessive opacity was discharging from an oven baking cores containing 3 percent fuel oil and 1.5 percent core oil at 500°F. The core binder was modified so that the cores contained 1.5 percent kerosene and 1.5 percent core oil, and the baking temperature was reduced to 400°F. After these modifications, no visible emissions were discharged from the oven.

When it is not feasible or possible to reduce excessive emissions from an oven by modifying the core mix or the baking temperature, afterburners are the only control devices that have proved effective. Since the quantity and concentration of the contaminants in the oven effluent are small, no precleaners or flashback devices are needed.

Afterburners that have been used for controlling the emissions from core ovens are predominantly of the direct-flame type. The burners are normally designed to be capable of reaching a temperature of at least 1,200°F under maximum load conditions. For most operations, 1,200°F completely controls all visible emissions and practically all odors.

The afterburner should be designed to have a maximum possible flame contact with the gases to be controlled and it should be of sufficient size to have a gas retention time of at least 0.3 second. Most authorities agree that the length-to-diameter ratio should be in the range of 1-1/2 to 4.

In some instances, particularly on larger core ovens, catalytic afterburners have been used to control the emissions. With inlet temperatures of from 600° to 650°F, all visible emissions and most of the odors were controlled. When catalytic afterburners are used, however, care must be taken to keep the catalyst in good condition; otherwise, partial oxidation can result in the discharge of combustion contaminants more objectionable than the oven effluent.

FOUNDRY SAND-HANDLING EQUIPMENT

A foundry sand-handling system consists of a device for separating the casting from the mold, and equipment for reconditioning the sand. The separating device is usually a mechanically vibrated grate called a shakeout. For small castings a manual shakeout may be used.

TYPES OF EQUIPMENT

The minimum equipment required for reconditioning the sand is a screen for removing oversize particles, and a mixer-muller where clay and water are combined with the sand to render it ready for remolding. In addition, equipment may be used to perform the following functions: Sand cooling, oversize crushing, fines removal, adherent coating removal, and conveying. A typical sand-handling system is shown in Figure 214.

Both flat-deck screens and revolving, cylindrical screens are used for coarse-particle removal. Revolving screens can be ventilated at such a rate as to remove excess fines.

Sand cooling can be accomplished in a number of ways, depending upon the cooling requirements. The amount of cooling required depends mainly upon the ratio of metal to sand in the molds and on the rate of re-use of the sand. With low metal-to-sand and re-use ratios, no specific sand-cooling equipment is required. When considerable cooling is required, a rotary drum-type cooler is usually used. A stream of air drawn through the cascading sand both cools and removes fines.

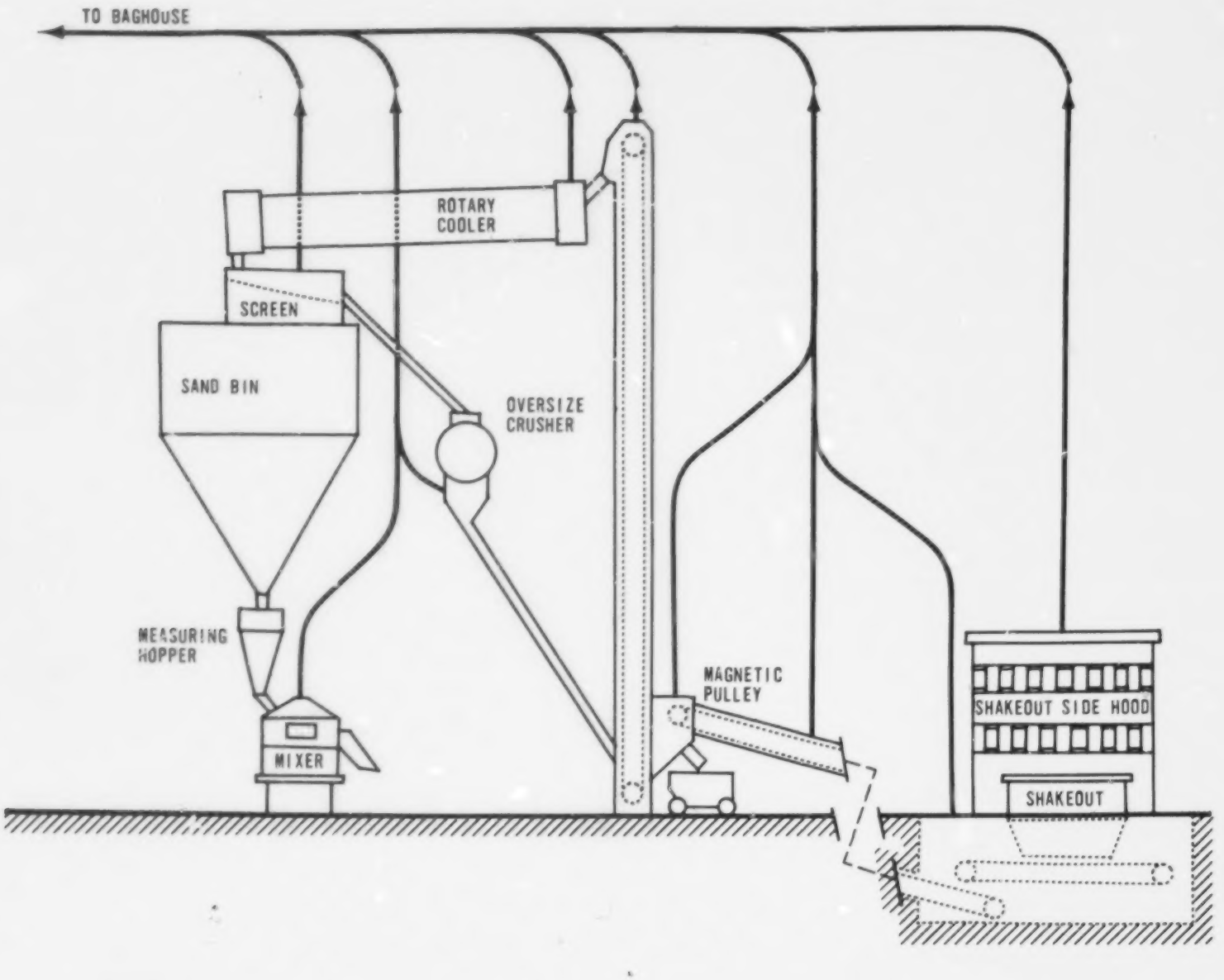


Figure 214. Typical foundry sand-handling system.

Oversize particles are hard agglomerates not broken up by the handling operations from the shakeout grate to the screen. Most of these are portions of baked cores. Many foundries discard the oversize particles, while others crush the agglomerates to recover the sand. A hammer- or screen-type mill is usually used for crushing.

Since molding sand is continuously reused, the grains become coated with a hard, adherent layer of clay and carbonaceous matter from the bonding materials used. In time the sand becomes unusable unless the coating is removed or a certain percentage of new sand is continuously added. Pneumatic reclamation is the method most widely used for coating removal. The sand is conveyed in a high-velocity airstream from a turbine-type blower and impinged on the inner surface of a conical target. Abrasion removes a portion of the coating material in each pass. The fines thus created are carried away in the airstream while the sand grains settle in an expansion chamber, as shown in Figure 215.

Foundry sand is usually conveyed by belt conveyors and bucket elevators, though pneumatic conveyors are used to some extent. Pneumatic conveying aids in cooling and fines removal.

The Air Pollution Problem

The air contaminants that may be emitted are dust from sand breakdown, and smoke and organic vapors from the decomposition of the core binders by the hot metal.

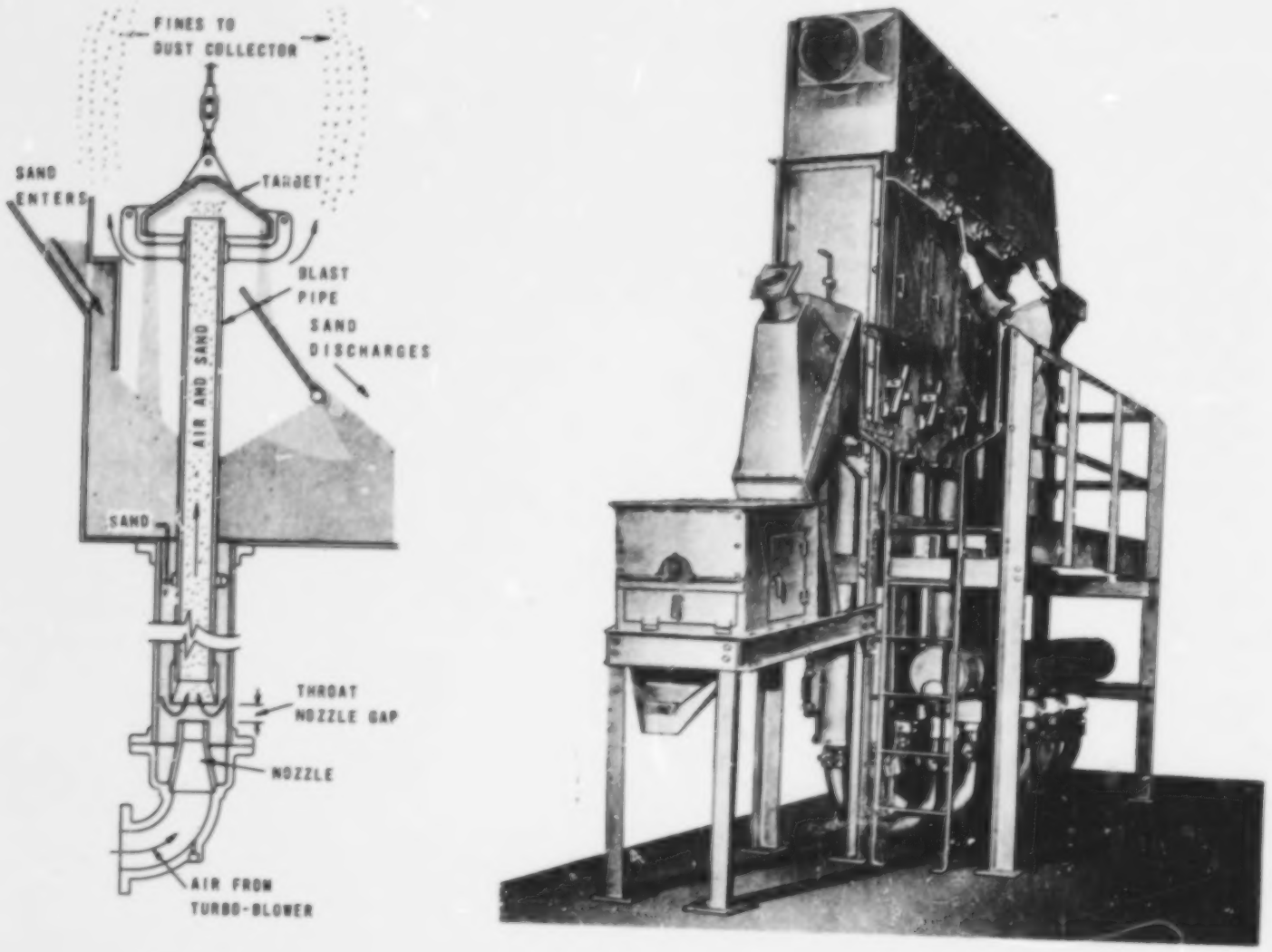


Figure 215. Pneumatic sand scrubber (National Engineering Co., Chicago, Ill.).

Among the factors that influence emission rates are size of casting, ratio of metal to sand, metal-pouring temperature, temperature of casting and sand at the shakeout, and handling methods. These factors have a great influence on the magnitude of the air pollution problem. For instance, a steel foundry making large castings, with a high metal-to-sand ratio requires a very efficient control system to prevent excessive emissions. A nonferrous foundry making small castings with a low metal-to-sand ratio, on the other hand, may not require any controls, since the bulk of the sand remains damp and emissions are negligible.

Hooding and Ventilation Requirements

The need for ventilation is determined by the same factors that influence emission rates. Minimum volumes of ventilation air required to ensure the adequate collection of the air contaminants are indicated in the discussion that follows on the various emission sources.

Shakeout grates

The amount of ventilation air required for a shakeout grate is determined largely by the type of hood or enclosure. The more nearly complete the enclosure, the less the required volume. When large flasks are handled by an overhead crane, an enclosing hood cannot be used, and a side or lateral hood is used instead. Recommended types of hood are shown in Figure 216 and Figure 217 (upper). Downdraft hoods are not recommended except for floor-dump type of operations where sand and castings are dropped from a roller conveyor to a gathering conveyor below the floor level (Manual of Exhaust Hood Designs, ____). An excessive exhaust volume is required to achieve adequate control in a downdraft hood because the indraft velocity is working against

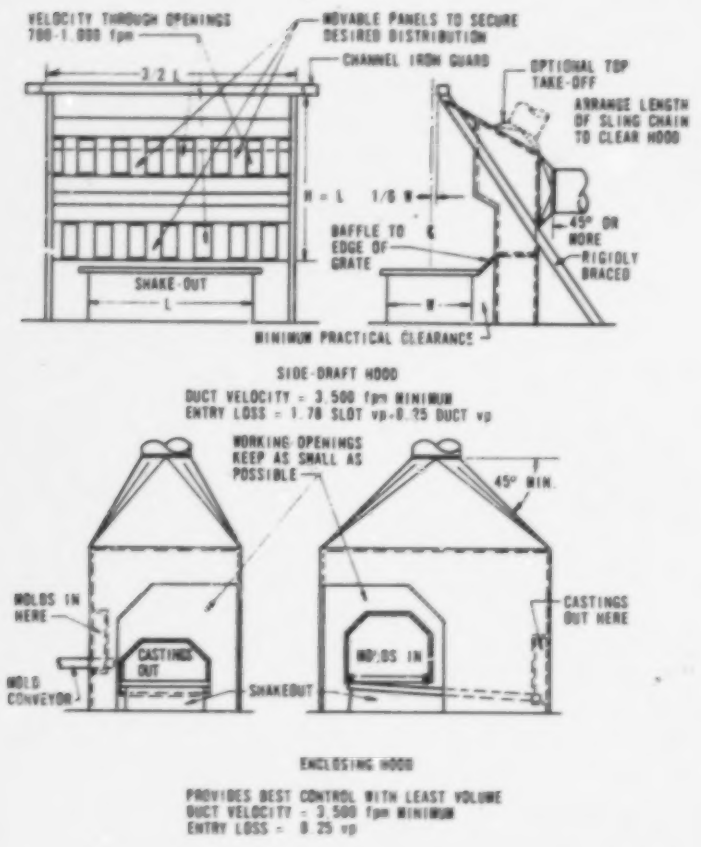


Figure 216. Foundry shakeout (Committee on Industrial Ventilation, 1960).

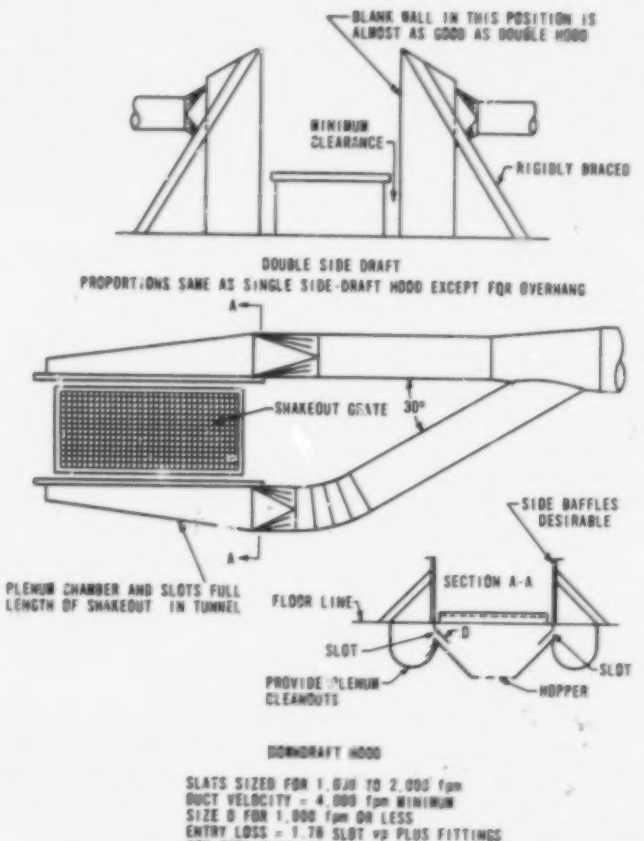

BLANK WALL IN THIS POSITION IS ALMOST AS GOOD AS DOUBLE HOOD
MINIMUM CLEARANCE
RIGIDLY BRACED
DOUBLE SIDE DRAFT
PROPORTIONS SAME AS SINGLE SIDE-DRAFT HOOD EXCEPT FOR OVERHANG
A
SHAKEOUT GRATE
30°
SIDE BAFFLES DESIRABLE
PLENUM CHAMBER AND SLOTS FULL LENGTH OF SHAKEOUT IN TUNNEL
SECTION A-A
FLOOR LINE
D
SLOT
SLOT
PROVIDE PLENUM CLEANOUTS
HOPPER
DOWNDRAFT HOOD
SLATS SIZED FOR 1,800 TO 2,000 fpm
DUCT VELOCITY = 4,000 fpm MINIMUM
SIZE D FOR 1,000 fpm OR LESS
ENTRY LOSS = 1.78 SLOT vp PLUS FITTINGS
FOR COOL CASTINGS ONLY
DIFFICULT TO PREVENT PLUGGING OR EXCESS FINES REMOVAL

Figure 217. Foundry shakeout (Committee on Industrial Ventilation, 1960).

the thermal bouyancy caused by the hot sand and casting. The indraft velocity is lowest where it is needed most--at the center of the grate. The exhaust volume requirements for the different types of hood are shown in Table 90. Shakeout hoppers should be exhausted with quantities of about 10 percent of the total exhaust volume listed in this table.

Other sand-handling equipment

Recommended ventilation volumes and hooding procedure for bucket elevators and belt conveyors are given in Figure 218; for sand screens, in Figure 219; and for mixer-mullers, in Figure 220. The ventilation requirement for rotary coolers is 400 cfm per square foot of open area. For crushers the requirement varies from 500 to 1,000 cfm per square foot of enclosure opening.

Air Pollution Control Equipment

The most important contaminant to be collected is dust, though smoke is sometimes intense enough to constitute a problem. Organic vapors and gases are usually not emitted in sufficient quantities to be bothersome. The collectors usually used are baghouses and scrubbers.

A baghouse in good condition collects all the dust and most of the smoke. A scrubber of moderately good efficiency collects the bulk of the dust, but the very fine dust and the smoke are not collected and in many cases leave a distinctly visible plume, sufficient to violate some control regulations. A baghouse, therefore, is the preferred collector when the maximum control measures are desired.

When only the shakeout is vented to a separate collector, there may be sufficient moisture in the gases in some cases to cause condensation and consequent blinding of the bags in a baghouse. When, however, all the equipment in a sand-handling system is served by a single exhaust system, ample ambient air is drawn into the system to preclude any moisture problem in the baghouse. The filtering velocity for this type of service should not exceed 3 fpm. Cotton sateen cloth is adequate for this service. A noncompartmented-type baghouse is adequate for most job shop foundries. For continuous-production foundries, a compartmented baghouse with automatic bag-shaking mechanisms gives the most trouble-free performance.

Table 90. EXHAUST VOLUME REQUIREMENTS FOR DIFFERENT TYPES OF HOOD VENTILATING SHAKEOUT GRATES

Type of hood	Exhaust requirement[a]	
	Hot castings	Cool castings
Enclosing	200 cfm/ft^2 of opening. At least 200 cfm/ft^2 of grate area	200 cfm/ft^2 of opening. At least 150 cfm/ft^2 of grate area
Enclosed two sides and 1/3 of top area	300 cfm/ft^2 of grate area	275 cfm/ft^2 of grate area
Side hood (as shown or equivalent)	400 to 500 cfm/ft^2 of grate area	350 to 400 cfm/ft^2 of grate area
Double side hood	400 cfm/ft^2 of grate area	300 cfm/ft^2 of grate area
Downdraft	600 cfm/ft^2 of grate area Not recommended	200 to 250 cfm/ft^2 of grate area

[a]Choose higher values when (1) castings are very hot, (2) sand-to-metal ratio is low, (3) crossdrafts are high.

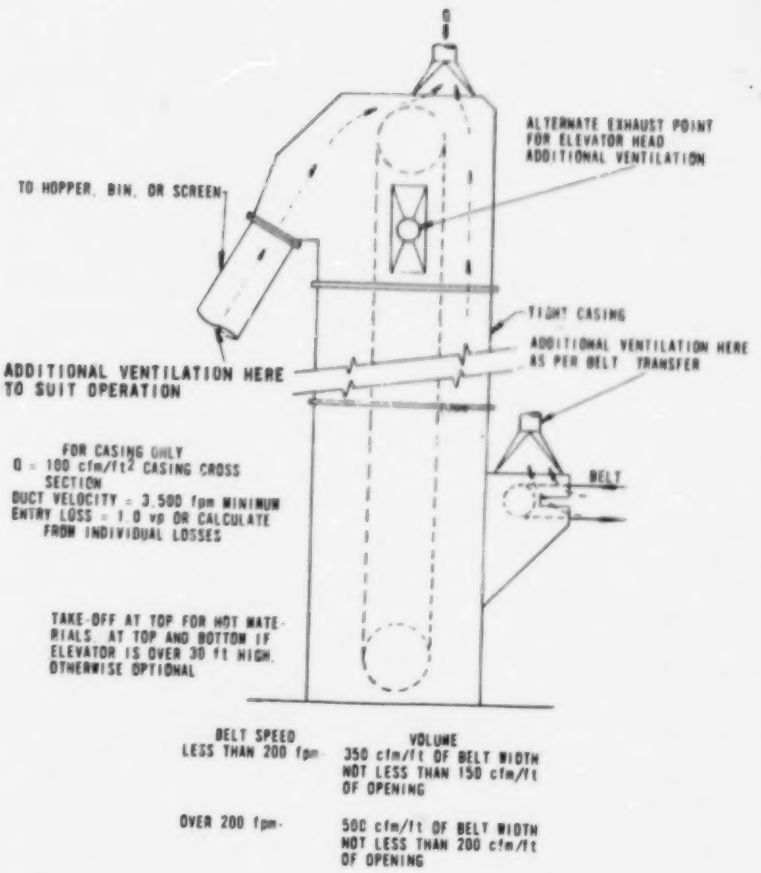

ALTERNATE EXHAUST POINT FOR ELEVATOR HEAD ADDITIONAL VENTILATION
TO HOPPER, BIN, OR SCREEN
TIGHT CASING
ADDITIONAL VENTILATION HERE AS PER BELT TRANSFER
ADDITIONAL VENTILATION HERE TO SUIT OPERATION
BELT
FOR CASING ONLY
Q = 100 cfm/ft² CASING CROSS SECTION
DUCT VELOCITY = 3,500 fpm MINIMUM
ENTRY LOSS = 1.0 vp OR CALCULATE FROM INDIVIDUAL LOSSES
TAKE-OFF AT TOP FOR HOT MATERIALS. AT TOP AND BOTTOM IF ELEVATOR IS OVER 30 ft HIGH. OTHERWISE OPTIONAL
BELT SPEED
LESS THAN 200 fpm
VOLUME
350 cfm/ft OF BELT WIDTH NOT LESS THAN 150 cfm/ft OF OPENING
OVER 200 fpm
500 cfm/ft OF BELT WIDTH NOT LESS THAN 200 cfm/ft OF OPENING

Figure 218. Bucket elevator ventilation (Committee on Industrial Ventilation, 1960).

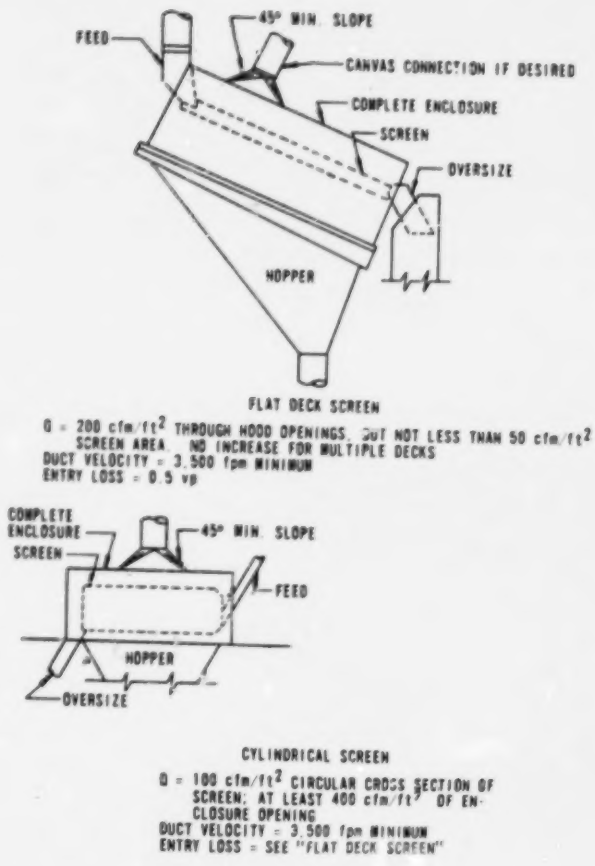
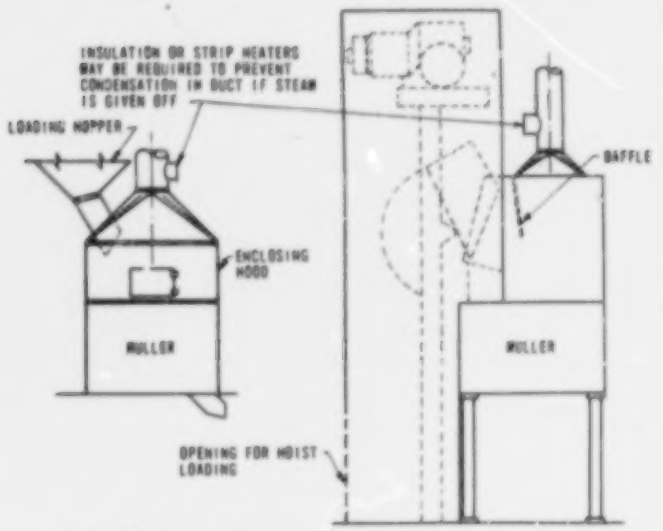

45° MIN. SLOPE
FEED
CANVAS CONNECTION IF DESIRED
COMPLETE ENCLOSURE
SCREEN
OVERSIZE
HOPPER
FLAT DECK SCREEN
Q = 200 cfm/ft² THROUGH HOOD OPENINGS, BUT NOT LESS THAN 50 cfm/ft² SCREEN AREA. NO INCREASE FOR MULTIPLE DECKS
DUCT VELOCITY = 3,500 fpm MINIMUM
ENTRY LOSS = 0.5 vp
COMPLETE ENCLOSURE
SCREEN
45° MIN. SLOPE
FEED
HOPPER
OVERSIZE
CYLINDRICAL SCREEN
Q = 100 cfm/ft² CIRCULAR CROSS SECTION OF SCREEN; AT LEAST 400 cfm/ft² OF ENCLOSURE OPENING
DUCT VELOCITY = 3,500 fpm MINIMUM
ENTRY LOSS = SEE "FLAT DECK SCREEN"

Figure 219. Screens (Committee on Industrial Ventilation, 1960).


INSULATION OR STRIP HEATERS MAY BE REQUIRED TO PREVENT CONDENSATION IN DUCT IF STEAM IS GIVEN OFF
LOADING HOPPER
ENCLOSING HOOD
MULLER
OPENING FOR HOIST LOADING
BAFFLE
MULLER

Q = 150 cfm ft^2 THROUGH ALL OPENINGS BUT NOT LESS THAN:

MIXER DIAMETER ft	EXHAUST cfm
4	650
6	900
8	1,200
10	1,500

DUCT VELOCITY = 3,500 fpm MINIMUM
ENTRY LOSS = 0.25 vp

NOTE: OTHER TYPES OF MIXERS. ENCLOSE AS MUCH AS POSSIBLE AND PROVIDE 150 cfm ft^2 OF REMAINING OPENINGS

Figure 220. Mixer and muller hood (Committee on Industrial Ventilation, 1960).

HEAT TREATING SYSTEMS

Heat treating involves the carefully controlled heating and cooling of solid metals and alloys for effecting certain desired changes in their physical properties. At elevated temperatures, various phase changes such as grain growth, recrystallization, and diffusion or migration of atoms take place in solid metals and alloys. If sufficient time is allowed at the elevated temperature, the process goes on until equilibrium is reached and some stable form of the metal or alloy is obtained. If, however, because of sudden and abrupt cooling, time is not sufficient to achieve equilibrium at the elevated temperature, then some intermediate or metastable form of the metal or alloys is obtained. The tendency to assume a stable form is always present and metals and alloys in a metastable form can be made to approach their stable form as closely as desired simply by reheating. The widely differing properties that can be imparted to solid metals and alloys in their stable and metastable forms give purpose to the whole process of heat treating.

In general, the methods used to heat treat both ferrous and nonferrous metals are fundamentally similar. These methods include hardening, quenching, annealing, tempering, normalizing ferrous metals, and refining grain of nonferrous metals. Also included in the category of heat treating are the various methods of case hardening steels by carburizing, cyaniding, nitriding, flame hardening, induction hardening, carbonitriding, siliconizing, and so forth.

HEAT TREATING EQUIPMENT

Furnaces or ovens, atmosphere generators, and quench tanks or spray tanks are representative of the equipment used for heat treating.

Furnaces for heat treating are of all sizes and shapes depending upon the temperature needed and upon the dimensions and the number of pieces to be treated. A furnace may be designed to operate continuously or batchwise. The controls may be either automatic or manual. These furnaces are known by descriptive names such as box, oven, pit, pot, rotary, tunnel, muffle, and others. Regardless of the name, they all have the following features in common: A steel outer shell, a refractory lining, a combustion or heating system, and a heavy door (either cast iron or reinforced steel with refractory lining) that may be opened from the top, the front, or from both the front and the back.

Atmosphere generators are used to supply a controlled environment inside the heat treating chamber of the furnace. The atmosphere needed may be either oxidizing, reducing, or neutral depending upon the particular metal or alloy undergoing heat treatment and upon the final physical properties desired in the metal or alloy after treatment. An atmosphere can be provided that will protect the surface of the metal during heat treatment so that subsequent cleaning and buffing of the part is minimized, or one can be provided that will cause the surface of the metal to be alloyed by diffusion with certain selected elements in order to alter the physical properties of the metal.

Quench tanks may be as simple as a tub of water or as elaborate as a well-engineered vessel equipped with properly designed means to circulate the quenching fluid and maintain the fluid at the correct temperature. The part to be quenched is either immersed into the fluid or is subjected to a spray that is dashed against the part so that no air or steam bubbles can remain attached to the hot metal and thereby cause soft spots. The fluid used for quenching may be water, oil, molten salt, liquid air, brine solution, and so forth. The purpose of quenching is to retain some metastable form of an alloy (pure metals are not affected by quenching) by rapidly cooling the alloy to some temperature below the transformation temperature.

The Air Pollution Problem

The heat treating process is currently regarded as only a minor source of air pollution. Nonetheless, air pollutants that may be emitted from

heat treating operations, and their origin, are as follows:

1. Smoke and products of incomplete combustion arising from the improper operation of a gas- or oil-fired combustion system;

2. vapors and fumes emanating from the volatilization of organic material on the metal parts being heat treated;

3. oil mists and fumes issuing from oil quenching baths (if water-soluble oils are used, the fumes will be a combination of steam and oil mist);

4. salt fumes emitted from molten salt pot furnaces;

5. gases, produced by atmosphere generators, used in the heat treating chamber of muffle furnaces. (Insignificant amounts occasionally leak out from some furnace openings that cannot be sealed, but somewhat larger amounts get into the surrounding air during purging and also during loading and unloading operations.)

Hooding and Ventilation Requirements

Hooding and ventilation systems designed for heat treating processes should be based on the rate at which the hot, contaminated air is delivered to the receiving face of the exhaust hood. To prevent the hot, contaminated air from spilling out around the edges of the exhaust hood, the rate at which the exhaust system draws in air must in all cases exceed the rate at which the hot, contaminated air is delivered to the exhaust system.

In the general case, a canopy hood mounted about 3 or 4 feet above a hot body has an excellent chance of capturing all the hot, contaminated air rising by convection from the hot body. The face area of a canopy hood such as this should be slightly larger than the maximum cross-sectional area of the hot body. In order to avoid the need for excessive exhaust capacity, it is advisable not to oversize the canopy hood face area.

If a canopy hood is mounted too high above the hot body, the column of hot, contaminated air is influenced by turbulence, and the column becomes more and more dilute by mixing with the surrounding air. Consequently the exhaust capacity must be sufficient to handle this entire volume of diluted, contaminated air. This is an inefficient way to collect hot, contaminated air.

Many variations of canopy hoods are used because of the many types of heat treating furnaces employed. Lateral-type hoods are also used. General features of design of hoods for these hot processes are discussed in Chapter 3.

Air Pollution Control Equipment

The following methods effectively prevent and control emissions resulting from heat treating operations.

1. Proper selection of furnace burners and fuels along with observance of correct operating procedures will eliminate smoke and products of incomplete combustion as a source of air pollution. (See Chapter 9.)

2. Removal of organic material adhering to metal parts to be heat treated by either steam cleaning or solvent degreasing before heat treating will eliminate this source of air pollution.

3. Mists and fumes issuing from oil quenching baths can be greatly reduced by selecting appropriate oils and by adequate cooling of the oil.

4. Baghouses are a satisfactory method of controlling salt fumes from molten salt pots. Particle sizes of fumes are usually between 0.2 and 2 microns but may vary from this range depending upon local factors such as temperature, humidity, turbulence, and agglomeration tendencies of the effluent. The fumes are slightly hygroscopic and corrosive; therefore, operation of the baghouse must be continuous to prevent blinding and deterioration of the bag cloth and corrosion of the metal structure. Acrylic-treated orlon is a satisfactory bag cloth because of its chemical and thermal resistance and its general physical stability. Filtering velocities should not be greater than 3 fpm. With these design features, collection efficiencies exceeding 95 percent are normally achieved.

5. Flame curtains placed at the open ends of continuous heat treating furnaces are effective in the control of any escaping, combustible gases used for controlling the atmosphere inside the furnace.

CHAPTER 7

MECHANICAL EQUIPMENT

HOT-MIX ASPHALT PAVING BATCH PLANTS

JOHN A. DANIELSON, Senior Air Pollution Engineer

ROY S. BROWN, JR., Air Pollution Engineer

CONCRETE-BATCHING PLANTS

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

JOHN L. MC GINNITY, Intermediate Air Pollution Engineer*

CEMENT-HANDLING EQUIPMENT

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

ROCK AND GRAVEL AGGREGATE PLANTS

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

MINERAL WOOL FURNACES

JOHN L. SPINKS, Air Pollution Engineer

PERLITE-EXPANDING FURNACES

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

FEED AND GRAIN MILLS

WILLIAM H. DONNELLY, Air Pollution Engineer

PNEUMATIC CONVEYING EQUIPMENT

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

DRIERS

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

JOHN L. MC GINNITY, Intermediate Air Pollution Engineer*

WOODWORKING EQUIPMENT

ROBERT GOLDBERG, Air Pollution Engineer†

EDWARD HIGGINS, Air Pollution Engineer*

RUBBER-COMPOUNDING EQUIPMENT

JOSEPH D'IMPERIO, Air Pollution Engineer

ASPHALT ROOFING FELT-SATURATORS

SANFORD M. WEISS, Senior Air Pollution Engineer

SOLVENT DEGREASERS

ROBERT T. WALSH, Senior Air Pollution Engineer

SURFACE-COATING OPERATIONS

SANFORD M. WEISS, Senior Air Pollution Engineer

PIPE-COATING EQUIPMENT

HARRY E. CHATFIELD, Air Pollution Engineer

DRY CLEANING EQUIPMENT

WILLIAM C. BAILOR, Air Pollution Engineer

ABRASIVE BLAST CLEANING

EDWIN J. VINCENT, Intermediate Air Pollution Engineer

ZINC-GALVANIZING EQUIPMENT

GEORGE THOMAS, Intermediate Air Pollution Engineer

*Now with National Center for Air Pollution Control, Public Health Service, U.S. Department of Health, Education, and Welfare, Cincinnati, Ohio.

†Now with the Public Health Service, U.S. Department of Health, Education, and Welfare, St. Glenville, Illinois.

‡Now with New York-New Jersey Air Pollution Abatement Activity, National Center for Air Pollution Control, Public Health Service, U.S. Department of Health, Education, and Welfare, Raritan Depot, Metuchen, New Jersey.

CHAPTER 7

MECHANICAL EQUIPMENT

HOT-MIX ASPHALT PAVING BATCH PLANTS

INTRODUCTION

Hot-mix asphalt paving consists of a combination of aggregates* uniformly mixed and coated with asphalt cement. An asphalt batch plant is used to heat, mix, and combine the aggregate and asphalt in the proper proportions to give the desired paving mix. After the material is mixed, it is transported to the paving site and spread as a loosely compacted layer with a uniformly smooth surface. While still hot, the material is compacted and densified by heavy motor-driven rollers to produce a smooth, well-compacted course.

Asphalt paving mixes may be produced from a wide range of aggregate combinations, each having particular characteristics and suited to specific design and construction uses. Aside from the amount and grade of asphalt cement used, the principal characteristics of the mix are determined by the relative amounts of:

Coarse aggregate (retained on No. 8-mesh sieve),

fine aggregate (passing No. 8-mesh sieve), and

mineral dust (passing No. 200-mesh sieve).

The aggregate composition may vary from a coarse-textured mix having a predominance of coarse aggregate to a fine-textured mix having a predominance of fine aggregate. The Asphalt Institute (1957) classifies hot-mix asphalt paving according to the relative amounts of coarse aggregate, fine aggregate, and mineral dust. The general limits for each mix type are shown in Table 91. The compositions used within each mix type are shown in Tables 92 and 93.

Raw Materials Used

Aggregates of all sizes up to 2-1/2 inches are used in hot-mix asphalt paving. The coarse aggregates usually consist of crushed stone, crushed slag, crushed gravel, or combinations thereof, or of material such as decomposed granite naturally occurring in a fractured condition, or of a highly angular natural aggregate with a pitted or rough surface texture. The fine aggregates usually consist of natural sand and may contain added materials such as crushed stone, slag, or gravel. All aggregates must be free from coatings of clay, silt, or other objectionable matter and should not contain clay particles or other fine materials. The aggregate must also meet tests for soundness (ASTM designation C88) and wearability (ASTM designation C131).

Mineral filler is used in some types of paving. It usually consists of finely ground particles of crushed rock, limestone, hydrated lime, Portland cement, or other nonplastic mineral matter. A minimum of 65 percent of this material must pass a 200-mesh sieve. Another name for mineral filler is mineral dust.

Asphalt cement is used in amounts of 3 to 12 percent by weight and is made from refined petroleum. It is a solid at ambient temperature but is usually used as a liquid at 275° to 325°F. One property measurement used in selecting an asphalt cement is the "penetration" as determined by ASTM Method D5. The most common penetration grades used in asphalt paving are 60 to 70, 85 to 100, and 120 to 150. The grade used depends upon the type of aggregate, the paving use, and the climatic conditions.

Basic Equipment

A typical hot-mix asphalt paving batch plant usually consists of an oil- or gas-fired rotary drier, a screening and classifying system, weigh boxes for asphalt cement and aggregate, a mixer, and the necessary conveying equipment consisting of bucket elevators and belt conveyors. Equipment for the storage of sand, gravel, asphalt cement, and fuel oil is provided in most plants. Heaters for the asphalt cement and fuel oil tanks are also used.

Plant Operation

Plants vary in size. The majority in Los Angeles County produce 4,000-pound batches and have production rates of 100 to 150 tons of asphalt paving mix per hour. Some of the newer plants are 6,000-pound batch size and are capable of producing 150 to 250 tons per hour.

* Aggregate is a term used to describe the solid mineral load-bearing constituents of asphalt paving such as sand particles and fragments of stone, gravel, and so forth.

Table 91. CLASSIFICATION OF HOT-MIX ASPHALT PAVING
(The Asphalt Institute, 1957)

Paving mix designation		Maximum size aggregate normally used	
Type	Description	Surface and leveling mixes	Base, binder, and leveling mixes
I	Macadam		2-1/2 in.
II	Open graded	3/8 to 3/4 in.	3/4 to 1-1/2 in.
III	Coarse graded	1/2 to 3/4 in.	3/4 to 1-1/2 in.
IV	Dense graded	1/2 to 1 in.	1 to 1-1/2 in.
V	Fine graded	1/2 to 3/4 in.	3/4 in.
VI	Stone sheet	1/2 to 3/4 in.	3/4 in.
VII	Sand sheet	3/8 in.	3/8 in.
VIII	Fine sheet	No. 4	No. 4

[a]Critical zone - Dust contents in this region should not be used without a substantial background of experience with such mixes and/or suitable justification by laboratory design tests.

[b]Intermediate zone - Dust contents in this region sometimes used in surface and leveling mixes as well as in base and binder mixes.

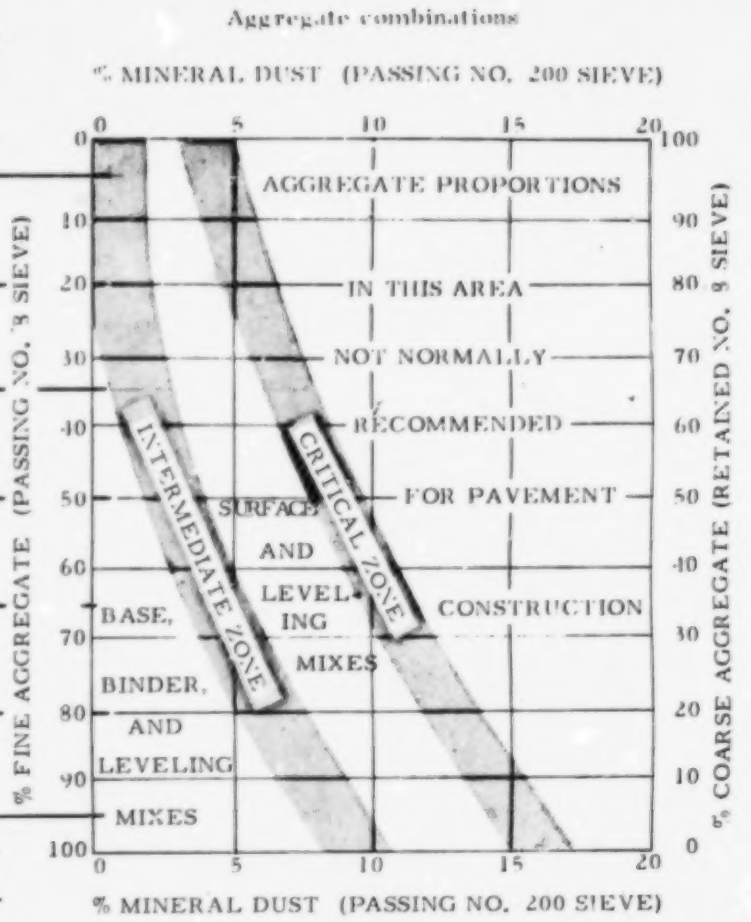


Figure 221 is a flow diagram of a typical plant. Aggregate is usually conveyed from the storage bins to the rotary drier by means of a belt conveyor and bucket elevator. The drier is usually either oil- or gas-fired and heats the aggregate to temperatures ranging from 250° to 350°F. The dried aggregate is conveyed by a bucket elevator to the screening equipment where it is classified and dumped into elevated storage bins. Selected amounts of the proper size aggregate are dropped from the storage bins to the weigh hopper. The weighed aggregate is then dropped into the mixer along with hot asphalt cement. The batch is mixed and then dumped into waiting trucks for transportation to the paving site. Mineral filler can be added directly to the weigh hopper by means of an auxiliary bucket elevator and screw conveyor.

Fine dust in the combustion gases from the rotary drier is partially recovered in a precleaner and discharged continuously into the hot dried aggregate leaving the drier.

THE AIR POLLUTION PROBLEM

The largest source of dust emissions is the rotary drier. Other sources are the hot aggregate bucket elevator, the vibrating screens, the hot aggregate bins, the aggregate weigh hopper, and the mixer. Rotary drier emissions up to 6,700 pounds per hour have been measured, as shown in Table 94. In one plant, 2,000 pounds of dust per hour was collected from the discharge of the secondary dust sources, that is, the vibrating screens, hot aggregate bins, the aggregate weigh hopper, and the mixer.

Table 92. COMPILATION OF SUGGESTED MIX COMPOSITIONS (The Asphalt Institute, 1957)

Mix type		Aggregate by size in mix, %												Asphalt, %
		1-1/2 in.	1 in.	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	
Mix seal	II a					100	40 to 85	5 to 20					0 to 4	4.0 to 8.0
	II b					70 to 100	20 to 40	5 to 20					0 to 4	4.0 to 8.0
	II c				100	70 to 100	20 to 40	5 to 20					0 to 4	4.0 to 8.0
S	III a			100	70 to 100	45 to 75	20 to 40	5 to 20					0 to 4	3.0 to 6.0
u	III b				100	75 to 100	35 to 55	20 to 35		10 to 22	6 to 16	4 to 12	2 to 8	3.0 to 6.0
r	IV a			100	75 to 100	60 to 80	35 to 55	20 to 35		10 to 22	6 to 16	4 to 12	2 to 8	3.0 to 6.0
f	IV b				100	80 to 100	55 to 75	35 to 50		18 to 29	13 to 23	8 to 16	4 to 10	3.5 to 7.0
a	IV c			100	80 to 100	70 to 90	50 to 70	35 to 50		18 to 29	13 to 23	8 to 16	4 to 10	3.5 to 7.0
c	V a		100	80 to 100		60 to 80	48 to 65	35 to 50		19 to 30	13 to 23	7 to 15	0 to 8	3.5 to 7.0
e	V b[a]				100	85 to 100	65 to 80	50 to 65	37 to 52	25 to 40	18 to 30	10 to 20	3 to 10	4.0 to 7.5
	VI a			100	85 to 100		65 to 80	50 to 65	37 to 52	25 to 40	18 to 30	10 to 20	3 to 10	4.0 to 7.5
	VI b[a]				100	85 to 100		65 to 80	50 to 70	35 to 60	25 to 48	15 to 30	6 to 12	4.5 to 8.5
	VII a[a]					85 to 100		65 to 80	47 to 68	30 to 55	20 to 40	10 to 25	3 to 8	4.5 to 8.5
	VIII a					100	85 to 100	80 to 95	70 to 89	55 to 80	30 to 60	10 to 35	4 to 14	6.0 to 11.0
							100	95 to 100	85 to 98	70 to 95	40 to 75	20 to 40	8 to 16	6.5 to 12.0

[a]May be used for base where coarse aggregate is not economically available.

Table 93. COMPILATION OF SUGGESTED MIX COMPOSITIONS (The Asphalt Institute, 1957)

Mix type	2-1/2 in.	1-1/2 in.	1 in.	3/4 in.	1/2 in.	3/8 in.	No. 4	No. 8	No. 16	No. 30	No. 50	No. 100	No. 200	Asphalt, %
Binder														
II c				100	70 to 100	45 to 75	20 to 40	5 to 20					0 to 4	3.0 to 6.0
II d			100	70 to 100		35 to 60	15 to 35	5 to 20					0 to 4	3.0 to 6.0
III b				100	75 to 100	60 to 85	35 to 55	20 to 35		10 to 22	6 to 16	4 to 12	2 to 8	3.0 to 6.0
III c				100	75 to 100	60 to 85	30 to 50	20 to 35		5 to 20	3 to 12	2 to 8	0 to 4	3.0 to 6.0
III d			100	75 to 100		45 to 70	30 to 50	20 to 35		5 to 20	3 to 12	2 to 8	0 to 4	3.0 to 6.0
IV c			100	80 to 100		60 to 80	48 to 65	35 to 50		19 to 30	13 to 23	7 to 15	0 to 8	3.5 to 7.0
Leveling														
III b				100	75 to 100	60 to 85	35 to 55	20 to 35		10 to 22	6 to 16	4 to 12	2 to 8	3.0 to 6.0
V b[a]				100	85 to 100		65 to 80	50 to 65	37 to 52	25 to 40	18 to 30	10 to 20	3 to 10	4.0 to 7.5
VI b[a]				100		85 to 100		65 to 80	47 to 68	30 to 55	20 to 40	10 to 25	3 to 8	4.5 to 8.5
Base														
I a	100	35 to 70		0 to 15				0 to 5					0 to 3	3.0 to 4.5
II d			100	70 to 100		35 to 60	15 to 35	5 to 20					0 to 4	3.0 to 6.0
II e		100	70 to 100	50 to 80		25 to 50	10 to 30	5 to 20					0 to 4	3.0 to 6.0
III d			100	75 to 100		45 to 70	30 to 50	20 to 35		5 to 20	3 to 12	2 to 8	0 to 4	3.0 to 6.0
III e		100	75 to 100	60 to 85		40 to 65	30 to 50	20 to 35		5 to 20	3 to 12	2 to 8	0 to 4	3.0 to 6.0
IV d		100	80 to 100	70 to 90		55 to 75	45 to 62	35 to 50		19 to 30	13 to 23	7 to 15	0 to 8	3.5 to 7.0

[a]May be used for base where coarse aggregate is not economically available.

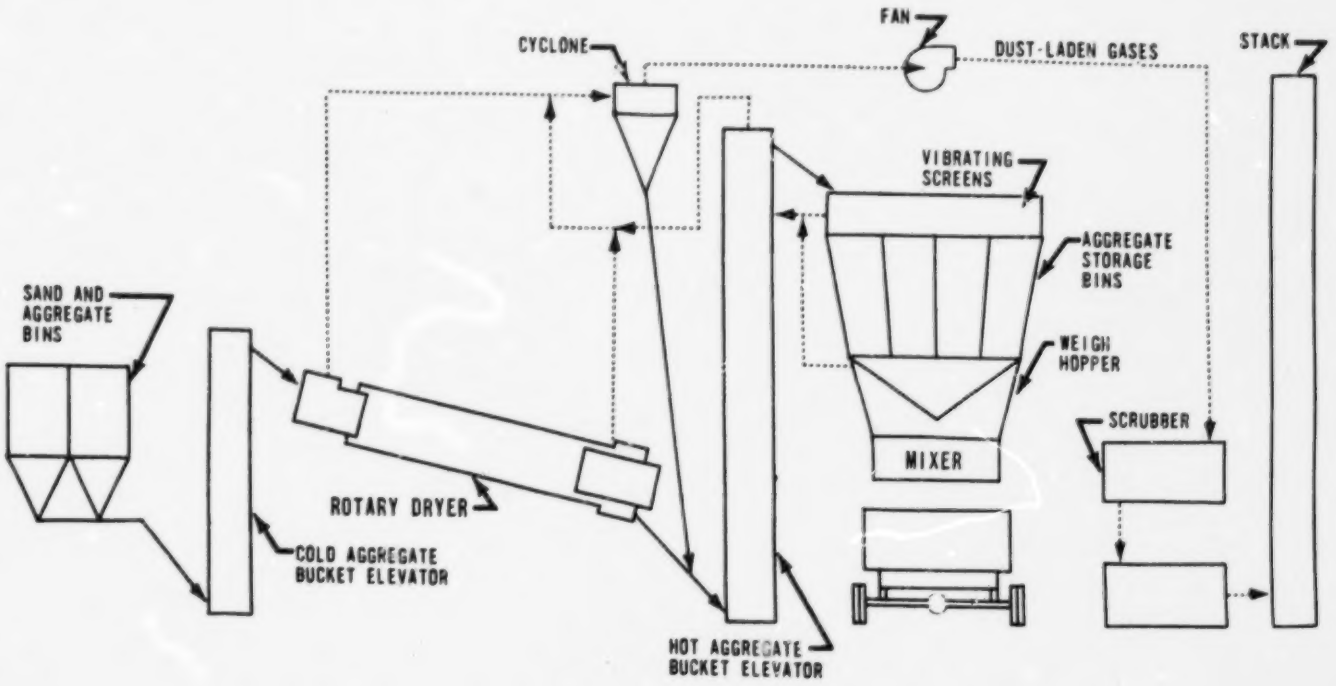


Figure 221. Flow diagram of a typical hot-mix asphalt paving batch plant.

Table 94. DUST AND FUME DISCHARGE FROM ASPHALT BATCH PLANTS

Test No.	C-426		C-537	
Batch plant data				
Mixer capacity, lb	6,000		6,000	
Process weight, lb/hr	364,000		346,000	
Drier fuel	Oil, PS300		Oil, PS300	
Type of mix	City street, surface		Highway, surface	
Aggregate feed to drier, wt %				
+10 mesh	70.8		68.1	
-10 to +100 mesh	24.7		28.9	
-100 to +200 mesh	1.7		1.4	
-200 mesh	2.8		1.6	
Dust and fume data	Vent line[a]	Drier	Vent line[a]	Drier
Gas volume, scfm	2,800	21,000	3,715	22,050
Gas temperature, °F	215	180	200	430
Dust loading, lb/hr	2,000	6,700	740	4,720
Dust loading, grains/scf	81.8	37.2	23.29	24.98
Sieve analysis of dust, wt %				
+100 mesh	4.3	17.0	0.5	18.9
-100 to +200 mesh	6.5	25.2	4.6	32.2
-200 mesh	89.2	57.8	94.9	48.9
Particle size of -200 mesh				
0 to 5 μ, wt %	19.3	10.1	18.8	9.2
5 to 10 μ, wt %	20.4	11.0	27.6	12.3
10 to 20 μ, wt %	21.0	11.0	40.4	22.7
20 to 50 μ, wt %	25.1	21.4	12.1	49.3
> 50 μ, wt %	14.2	46.5	1.1	6.5

[a]Vent line serves hot elevator, screens, bin, weigh hopper, and mixer.

Drier dust emissions increase with air mass velocity, increasing rate of rotation, and feed rate, but are independent of drier slope (Friedman and Marshall, 1949). Particle size distribution of the drier feed has an appreciable effect on the discharge of dust. Tests show that about 55 percent of the minus 200-mesh fraction in the drier feed can be lost in processing. The dust emissions from the secondary sources vary with the amount of fine material in the feed and the mechanical condition of the equipment. Table 94 and Figure 222 give results of source tests of two typical plants. Particle size of the dust emissions and of the aggregate feed to the drier are also shown.

HOODING AND VENTILATION REQUIREMENTS

Dust pickup must be provided at all the sources of dust discharge. Total ventilation requirements vary according to the size of the plant. For a 6,000-pound-per-batch plant, 22,000 scfm is typical, of which 18,000 to 19,000 scfm is allotted for use in controlling the drier emissions. The top end of the drier must be closely hooded to provide for exhaust of the products of combustion and entrained dust. A ring-type hood located between the stationary portion of the burner housing and the drier provides satisfactory pickup at the lower end of the drier. An indraft velocity of 200 fpm should be provided at the annular opening between the circumference of the drier and the ring-type hood.

The secondary dust sources, that is, the elevator, vibrating screens, hot aggregate bins, weigh hopper, and mixer, are all totally enclosed, and hence, no separate hooding is required. Dust collection is provided by connecting this equipment through branch ducting to the main exhaust system. Approximately 3,000 to 3,500 scfm will adequately ventilate these secondary sources.

AIR POLLUTION CONTROL EQUIPMENT

Primary dust collection equipment usually consists of a cyclone. Twin or multiple cyclones are also used. The catch of the primary dust collector is returned to the hot bucket elevator where it continues on with the main bulk of the drier aggregate. The air discharge from the primary dust collector is ducted to the final dust collection system.

Two principal types of final control equipment have evolved from the many types employed over the years: The multiple centrifugal-type spray chamber (Figure 223) and the baffled-type spray tower

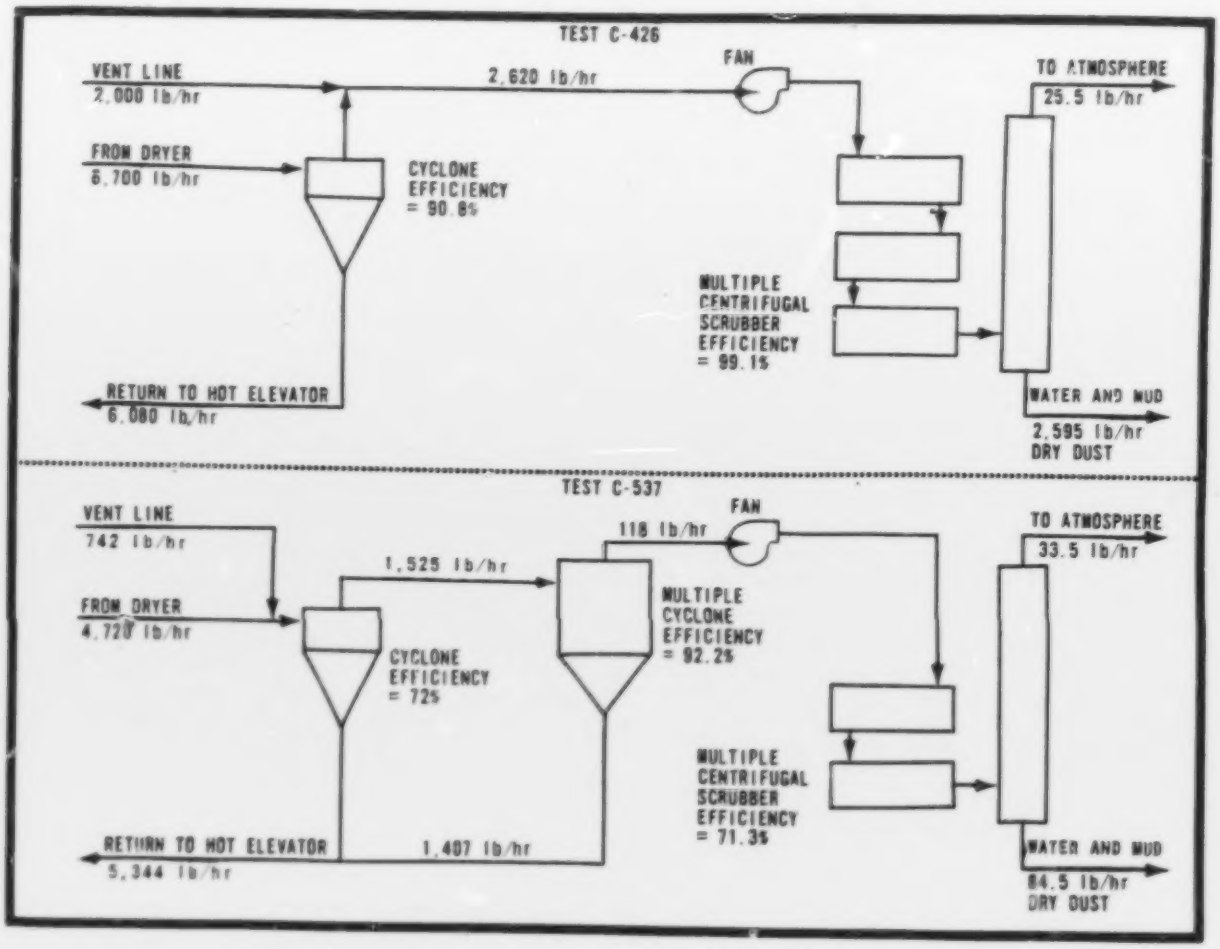


Figure 222. Test data on air pollution control equipment serving two hot-mix asphalt paving plants (vent line serves screens, hot bins, weigh hopper, and mixer).

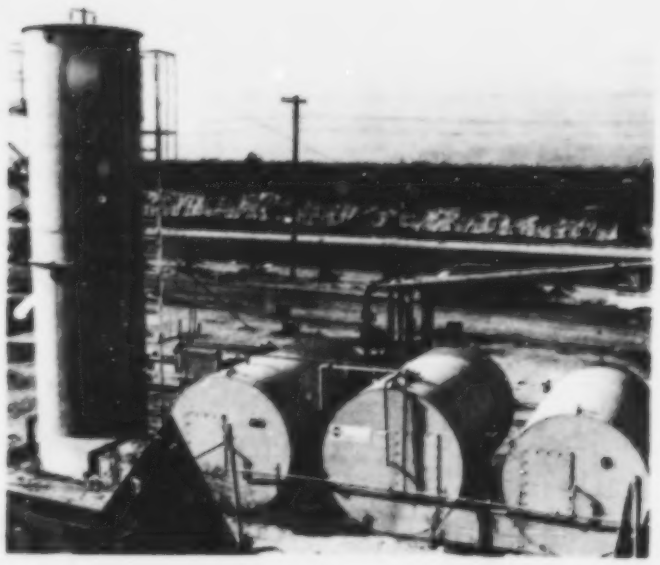


Figure 223. Typical multiple centrifugal-type scrubber serving a 4,000-pound-batch-capacity hot-mix asphalt paving plant.

(Figure 224). The multiple centrifugal-type spray chamber has proved the more efficient. It consists of two or more internally fluted, cylindrical spray chambers in which the dust-laden gases are admitted tangentially at high velocities. These chambers are each about the same size, that is, 6 feet in diameter by 15 feet in length, if two chambers are used, and 6 feet in diameter by 9 or 12 feet in length if three chambers are used. Usually 7 to 12 spray nozzles are evenly spaced within each chamber. The total water rate to the nozzles is usually about 70 to 250 gpm at 50 to 100 psi. In the baffled-type spray tower, there have been many variations and designs, but fundamentally, each consists of a chamber that is baffled to force the gases to travel in a sinuous path, which encourages impingement of the dust particles against the sides of the chamber and the baffles. Water spray nozzles are located among the baffles, and the water rate through the spray nozzles is usually between 100 to 300 gpm at 50 to 100 psi.

n both types of scrubber the water may be either fresh or recirculated. Settling pits or concrete tanks of sufficient capacity to allow most of the collected dust to settle out of the water are re-

Figure 224. Typical baffled-type spray tower serving a 4,000-pound-batch-capacity hot-mix asphalt paving plant (Griffith Company, Wilmington, Calif.).

quired with a system using recirculated water. The scrubber catch is usually hauled away and discarded. It is usually unsuitable for use as mineral filler in the paving mix because it contains organic matter and clay particles. The recirculated water may become acidic and corrosive, depending upon the amount of sulfur in the drier fuel, and must then be treated with chemicals to protect the scrubber and stack from corrosion. Caustic soda and lime have been used successfully for this purpose.

Variables Affecting Scrubber Emissions

In a recent study (Ingels et al., 1960), many source tests (see Table 95) on asphalt paving plants in Los Angeles County were used to correlate the major variables affecting stack losses. Significant variables include the aggregate fines feed rate (the minus 200-mesh fraction), the type of fuel fired in the drier, the scrubber's water-gas ratio,* and the type of scrubber used. Other, less important variables were also revealed in the study.

*The water-gas ratio is defined as the total quantity of water sprayed in gallons per 1,000 scf of effluent gas.

The effect of aggregate fines feed rate on stack emissions at constant water-gas ratio (an average value for test considered) is shown in Figure 225 for multiple centrifugal-type scrubbers and baffled tower scrubbers. Stack emissions increase linearly with an increase in the amount of minus 200-mesh material processed. These losses can be greatly reduced by using a clean or washed sand. The required fines content of the hot-mix asphalt paving is then obtained by adding mineral filler directly to the plant weigh hopper by means of an auxiliary bucket elevator and screw conveyor.

Most asphalt paving batch plants burn natural gas. When gas is not available, and if permitted by law, a heavy fuel oil (U.S. Grade No. 6 or heavier) is usually substituted. Dust emissions to the atmosphere from plants with air pollution control devices were found to be about 5.1 pounds per hour greater when the drier was fired with oil than they were when the drier was fired with natural gas. The difference is believed to represent particulate matter residing in, or formed by, the fuel oil, rather than additional dust from the drier. Similarly, the burning of heavy fuel oils in other kinds of combustion equipment results in greater emissions of particulate matter.

The amount of water fed to the scrubber is a very important consideration. The spray nozzles should

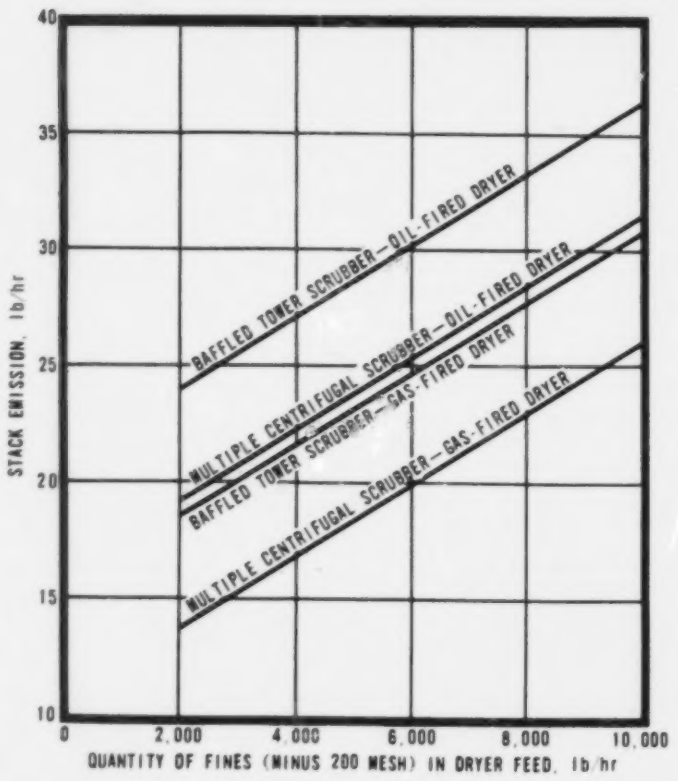


Figure 225. Effect of aggregate fines feed rate on stack emissions at average water-gas ratio (Ingels et al., 1960).

Table 95. TEST DATA FROM HOT-MIX ASPHALT PAVING PLANTS CONTROLLED BY SCRUBBERS

Test No.	Scrubber inlet dust loading, lb/hr	Stack emission, lb/hr	Aggregate fines rate,[a] lb/hr	Water-gas ratio, gal/1,000 scf	Overall scrubber efficiency, wt %	Type of scrubber[b]	Type of drier fuel	Production rate, tons/hr	Gas effluent volume, scfm
C-357	940	20.7	9,550	6.62	97.8	C	Oil	183.9	23,100
C-82	427	35.6	4,460	3.94	91.6	C	Oil	96.9	19,800
C-379	4,110	37.1	8,350	6.38	99.1	C	Oil	174.0	26,200
C-355	2,170	47.0	14,000	6.81	97.8	C	Oil	209.1	25,700
C-372B	121	19.2	2,290	10.99	84.2	C	Oil	142.9	18,200
C-372A	76	10.0	2,840	11.11	86.8	C	Gas	158.0	18,000
C-369	352	24.4	4,750	5.41	93.0	C	Oil	113.0	16,100
C-393	4,260	26.9	4,050	12.01	99.3	T	Oil	92.3	19,500
C-354	--	27.8	6,370	6.10	--	T	Oil	118.4	7,720
C-185	1,640	21.3	5,220	19.40	98.7	T	Oil	137.8	18,700
C-173	--	31.0	8,850	20.40	--	T	Oil	184.2	17,000
1	--	33.5	7,520	11.01	--	T	Oil	144.6	23,700
C-379	3,850	30.3	6,500	5.92	99.2	C	Gas	191.3	28,300
C-337	305	13.6	2,510	11.11	95.5	C	Oil	114.6	24,300
2	--	21.1	3,730	7.28	--	T	Gas	124.4	15,900
C-234	372	21.2	2,530	5.70	94.3	T	Gas	42.0	17,200
C-426	2,620	25.5	10,200	7.75	99.0	C	Oil	182.0	22,000
C-417	560	39.9	3,050	2.94	92.8	C	Oil	138.9	24,600
C-425	485	32.9	2,890	4.26	93.2	C	Oil	131.4	18,900
3	--	25.5	6,590	6.60	--	C	Gas	131.7	18,200
C-385	212	17.5	4,890	4.56	91.7	C	Oil	174.3	20,000
C-433	266	11.0	5,960	8.12	95.8	C	Gas	114.5	19,600
C-422(1)	--	26.6	7,140	4.90	--	C	Oil	198.0	21,000
C-422(2)	--	37.0	3,340	3.02	--	C	Oil	152.0	22,200
C-418	3,400	30.8	9,350	8.90	99.1	T	Oil	116.5	17,100
Averages		26.7	5,900		94.9				

[a] Quantity of fines (minus 200 mesh) in dryer feed.
[b] C = Multiple centrifugal-type spray chamber.
T = Baffled tower scrubber.

be located so as to cover the moving gas stream adequately with fine spray. Sufficient water should be used to cool the gases below the dew point. One typical scrubber tested had an inlet gas at 200°F with 16.8 percent water vapor content by volume, and an outlet gas at 131°F with 16.3 percent water vapor and saturated. The temperature at the gas outlet of efficient scrubbers rarely exceeds 140°F, and the gas is usually saturated with water vapor.

Figure 226 shows the effect of the scrubber's water-gas ratio on dust emissions with the aggregate fines feed rate held constant (an average value for the test considered). Efficient scrubbers use water at rates of 6 to 10 gallons per 1,000 standard cubic feet of gas. The efficiency falls off rapidly at water rates less than 6 gallons per 1,000 scf of gas. At rates of more than 10 gallons per 1,000 scf of gas, the efficiency still increases, but at a lesser rate.

Curves are presented in Figures 227 and 228 from which probable stack emissions can be predicted for oil- and gas-fired plants with either multiple centrifugal or baffled tower scrubbers. These curves present emissions for various scrubbers' water-gas ratios and aggregate fines rates. Emission predictions from these curves are accurate only for plants of the type and design already discussed.

The operation of the rotary drier is also an important variable. Dust emissions increase with an increase of air mass velocity through the drier. Obviously then, care should be taken to operate the drier without a great amount of excess air. This care effects fuel economy and reduces dust emissions from the drier.

The firing rate of the drier is determined by the amount of moisture in the aggregate and by the required hot aggregate temperature. The greater the aggregate moisture content, the greater the firing rate and the resulting dust emissions to the atmosphere. In some plants, the increase in moisture content of the flue gases may increase the efficiency of the scrubber sufficiently to offset the increase in dust emissions from the drier.

Scrubber efficiencies also vary according to the degree of precleaning done by the primary dust collector. Tests (such as those presented in Table 95) have shown that overall efficiency of the pre-

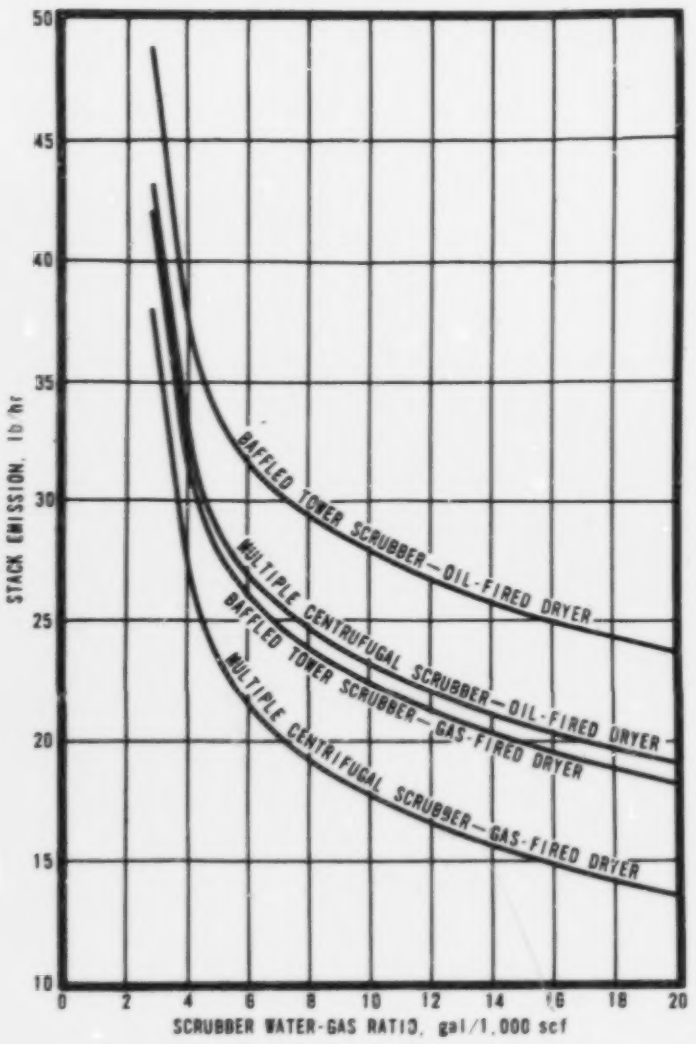

STACK EMISSION, lb/hr
SCRUBBER WATER-GAS RATIO, gal/1,000 scf
BAFFLED TOWER SCRUBBER—OIL-FIRED DRYER
MULTIPLE CENTRIFUGAL SCRUBBER—OIL-FIRED DRYER
BAFFLED TOWER SCRUBBER—GAS-FIRED DRYER
MULTIPLE CENTRIFUGAL SCRUBBER—GAS-FIRED DRYER

Figure 226. Effect of scrubber's water-gas ratio on stack emissions at average aggregate fines feed rate in the drier feed (Ingels et al., 1960).

cleaner and final collector varies only slightly with large variations in precleaner efficiency. Plants with less effective cyclone precleaning had, on the average, larger particles entering the scrubber, and consequently, show greater scrubber collection efficiencies. The principal advantage of an efficient precleaner is that the valuable fines collected can be discharged directly to the hot elevator for use in the paving mix. Furthermore, less dust is discharged to the scrubber, where more troublesome dust disposal problems are encountered.

Collection Efficiencies Attained

Collection efficiencies of cyclonic-type precleaners vary from approximately 70 to 90 percent on an overall weight basis. Scrubber efficiencies varying from 85 to nearly 100 percent have been found. Overall collection efficiencies usually vary between 95 and 100 percent.

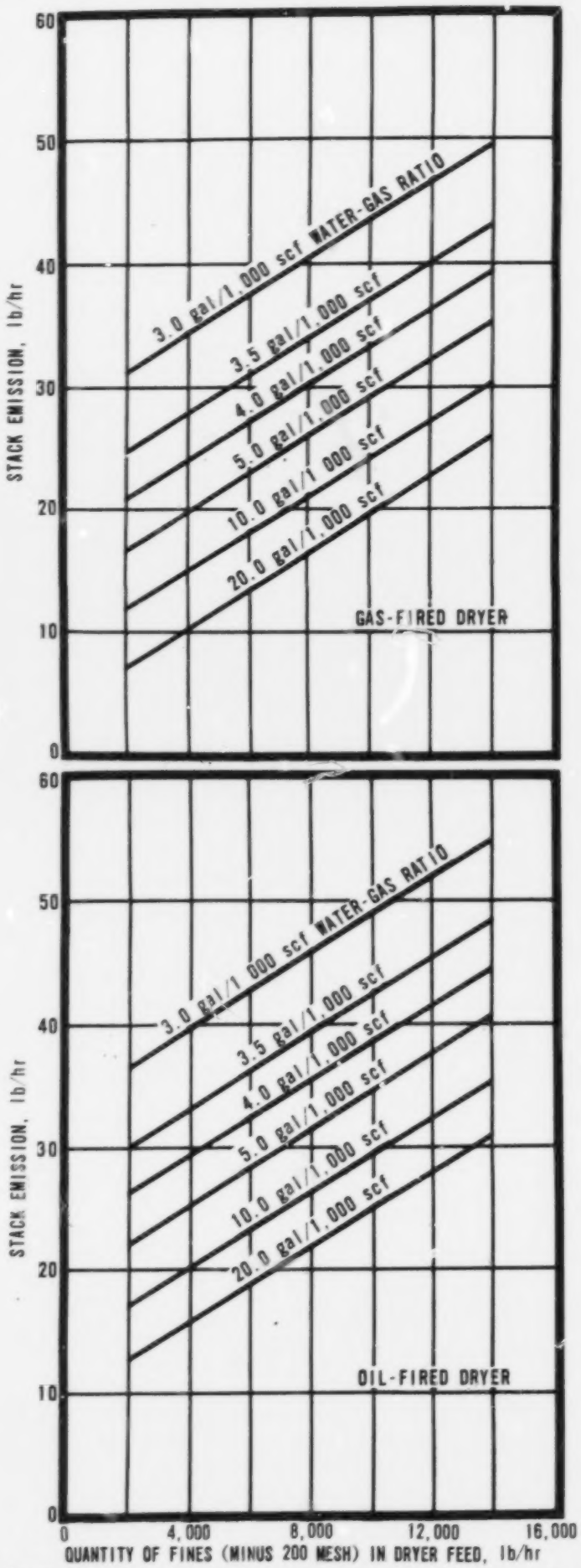


Figure 227. Emission prediction curves for multiple centrifugal scrubbers serving asphaltic concrete plants (Ingels et al., 1960).

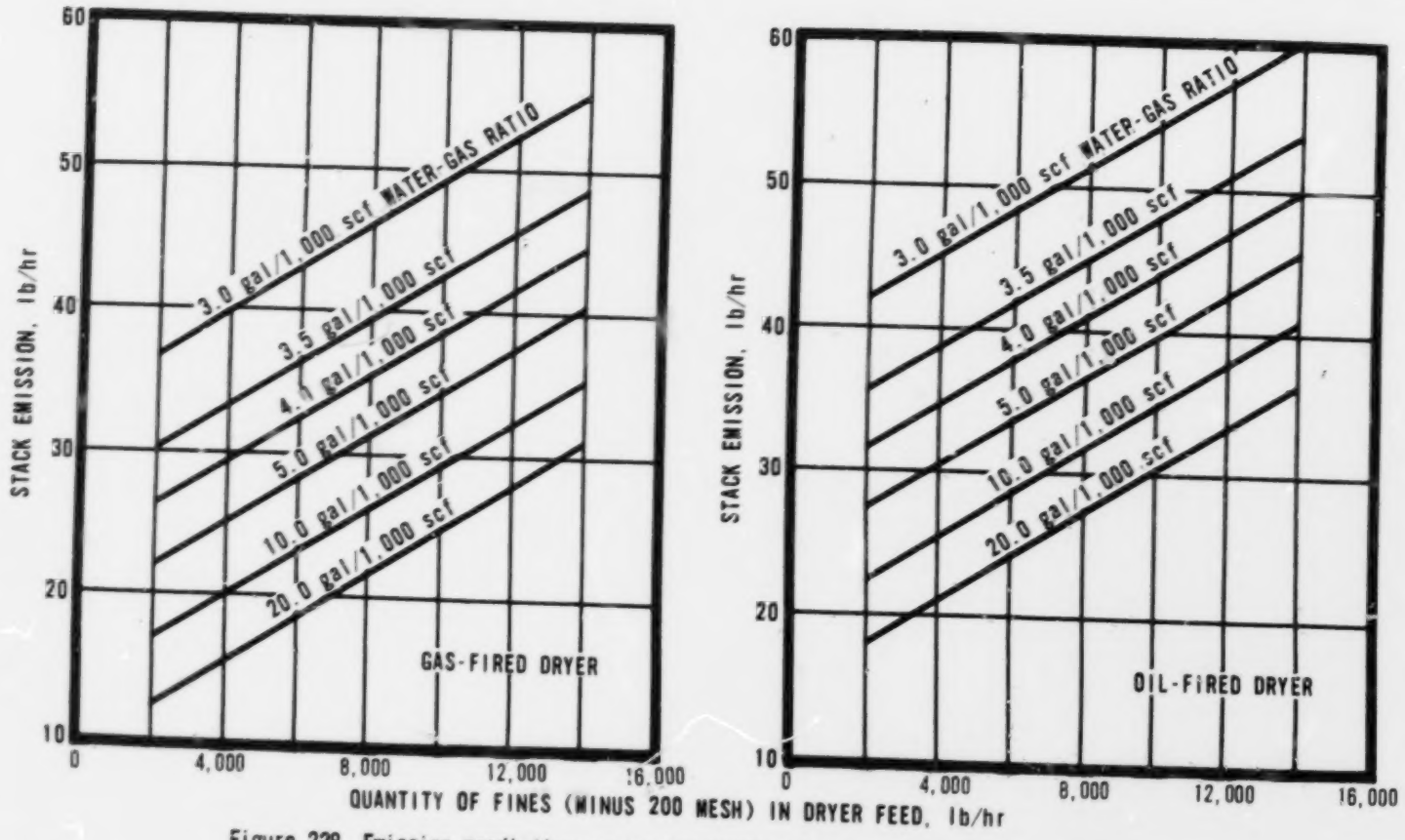


Figure 228. Emission prediction curves for baffled tower scrubbers serving asphaltic concrete plants (Ingels et al., 1960).

Collection efficiencies of a simple cyclone and a multiple cyclone for various particle sizes are shown in Table 96. Multiple cyclones achieve high efficiencies for particle sizes down to 5 microns, whereas single cyclones are very inefficient for particle sizes below 20 microns. The particle size data from this table are plotted on log-probability paper in Figure 229. This figure also shows the particle size distribution of the scrubber outlet. Other data on this installation have already been presented in Figure 222, test C-537.

Cost of Air Pollution Control Equipment

The cost of control equipment varies according to the manufacturer, location, and type of installation. A typical system consisting of a 12-foot-diameter cyclone, a twin- or triple-tube scrubber complete with ductwork, water pump, and fan will cost about $25,000 for a plant capable of handling 6,000-pound batches. If a multiple cyclone and provisions for recirculating the water are added, the total cost may approach $45,000.

Table 96. COLLECTION EFFICIENCY DATA FOR A CYCLONE AND A MULTIPLE CYCLONE SERVING A HOT-MIX PAVING PLANT

Dust particle size, μ	Test C-537 cyclone			Test C-537[a] multiple cyclone		
	Inlet, %	Outlet, %	Efficiency, %	Inlet, %	Outlet, %	Efficiency, %
0 to 5	6.2	19.3	13.3	19.3	57.0	77.1
5 to 10	9.4	31.9	5.4	31.9	34.0	91.7
10 to 20	13.8	31.6	36.1	31.6	8.8	97.8
20 to 50	22.9	15.1	81.6	15.1	9.2	99.9
50+	47.7	2.1	98.8	2.1	--	100.0
Dust loading lb/hr	5,463	1,525	72.1%	1,525	118.3	92.2%

[a]See Table 94, test C-537 for plant operating data.

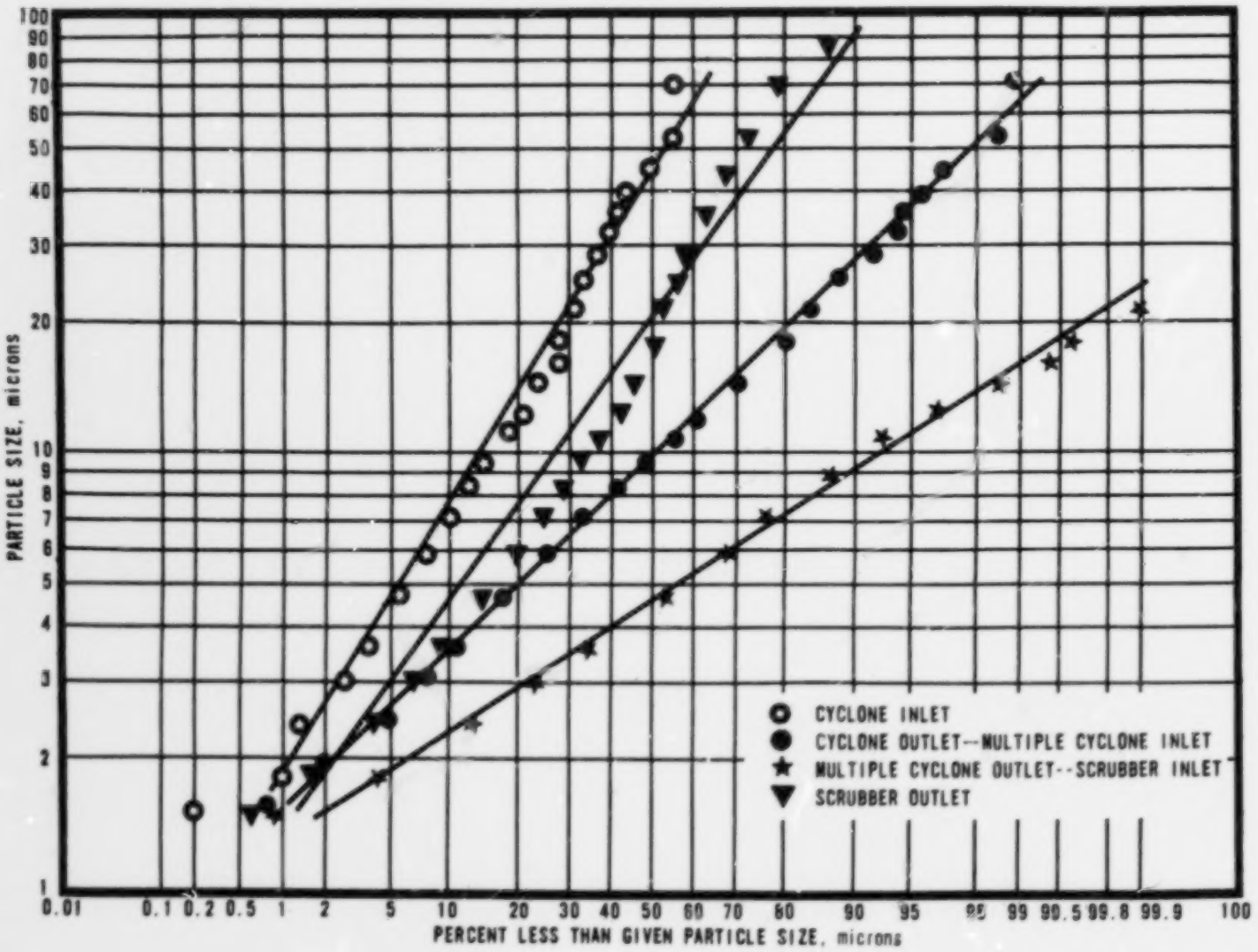


Figure 229. Plot of particle size of dust at the inlet and outlet of a cyclone and multiple cyclone from test C-537.

CONCRETE-BATCHING PLANTS

Concrete-batching plants store, convey, measure, and discharge the ingredients for making concrete to mixing or transportation equipment. One type is used to charge sand, aggregate, cement, and water to transit-mix trucks, which mix the batch en route to the site where the concrete is to be poured; this operation is known as "wet batching." Another type is used to charge the sand, aggregate, and cement to flat bed trucks, which transport the batch to paving machines where water is added and mixing takes place; this operation is known as "dry batching." A third type employs the use of a central mix plant, from which wet concrete is delivered to the pouring site in open dump trucks.

WET-CONCRETE-BATCHING PLANTS

In a typical wet-concrete-batching plant, sand and aggregates are elevated by belt conveyor or, clam shell crane, or bucket elevator to overhead storage bins. Cement from bottom-discharge hopper trucks is conveyed to an elevated storage silo. Sand and aggregates for a batch are weighed by successive additions from the overhead bins to a weigh hopper. Cement is delivered by a screw conveyor from the silo to a separate weigh hopper. The weighed aggregates and cement are dropped into a gathering hopper and flow into the receiving hopper to the transit-mix truck. At the same time, the required amount of water is injected into the flowing stream of solids. Details and variations of this general procedure will be discussed later.

The Air Pollution Problem

Dust, the air contaminant from wet-concrete-batching, results from the material used. Sand and aggregates for concrete production come directly from a rock and gravel plant where they are washed to remove silt and clay-like minerals. They thus

arrive at the batch plant in a moist condition and hence do not usually present a dust problem. When, however, lightweight aggregates are used, they do pose a problem. These materials are formed by thermal expansion of certain minerals. They leave the aggregate plant very dry and create considerable dust when handled. The simplest way to deal with this problem is to wet each load of aggregate thoroughly before it is dumped from the delivery truck. Attempts to spray the aggregate as it is being dumped have had very limited effectiveness.

If, therefore, wet or damp aggregate is used, practically all the dust generated from concrete-batching operations originates from the cement. Particle size distribution and other characteristics of the dust vary according to the grade of cement. A range of 10 to 20 percent by weight of particles of 5-micron size or less is typical for the various grades of cement. Bulk density ranges from 50 to 65 pounds per cubic foot of cement. Table 97 shows additional characteristics of three common grades of cement.

Table 97. CHARACTERISTICS OF THREE GRADES OF CEMENT

Distribution, μ	Cement, wt %		
	Grade I	Grade II	Grade III
0 to 5	13.2	9.6	21.8
5 to 10	15.1	16.6	22.5
10 to 20	25.7	18.8	26.7
20 to 40	29.0	36.6	23.6
40 to 50	7.0	10.4	5.4
50 to 66	5.0	6.0	0
66 to 99	4.0	2.0	0
99 to 250	1.0	0	0
250 (60 mesh)	0	0	0
Bulk density, lb/ft^3	54.0	51.5	62.0
Specific gravity, g/cm^3 at 82°F	3.3	3.3	3.3

Cement dust can be emitted from several points. The receiving hopper, the elevator, and the silo are the points of possible emission from the cement-receiving station. Other points of possible dust emission are the cement weigh hopper, the gathering hopper, and the mixer.

Air Pollution Control Equipment

Cement-receiving and storage system

A typical cement-receiving and storage system is shown in Figure 230. The receiving hopper is at or below ground level. If it is designed to fit the canvas discharge tube of the hopper truck, little or no dust is emitted at this point. After a brief initial puff of dust, the hopper fills completely and the cement flows from the truck without any free fall. Cement elevators are either the vertical-screw type or the enclosed-bucket type. Neither emits any dust if in good condition. The cement silo must be vented to allow the air displaced by the cement to escape. Unless this vent is filtered, a significant amount of dust escapes.

Figure 230 shows one type of filter. It consists of a cloth tube with a stack and weathercap for protection. The pulley arrangement allows it to be shaken from the ground so that the accumulated layer of dust on the inside of the cloth tube can be periodically removed. The cloth's area should be sufficient to provide a filtering velocity of 3 fpm, based upon the displaced air rate.

Many concrete batch plants now receive cement pneumatically from trucks equipped with compressors and pneumatic delivery tubes. In these plants, a single filtered vent used for the gravity filling of cement has proved inadequate, and other methods of control are required. In this pneumatic delivery, the volume of conveying air is approximately 350 cfm during most of the loading cycle and increases to 700 cfm at the end of the cycle.

To control this volume of air, it is best to install a small conventional cotton sateen baghouse with a filtering area of 3 fpm (approximately 200 square feet of cloth area) to vent the cement silo. The baghouse should be equipped with a blower to relieve the pressure built up within the silo. A mechanical shaking mechanism also should be provided to prevent cement from blinding the filter cloth of the baghouse.

Another less expensive type of control device is to mount a bank of approximately four simple filtered vents atop the silo. The filtering area should not exceed 7 fpm, giving an area of approximately 100 square feet for the 700 cfm of air encountered at the end of the cycle. The filter design must include a shaking mechanism to prevent blinding of the filter cloth. The major dis-

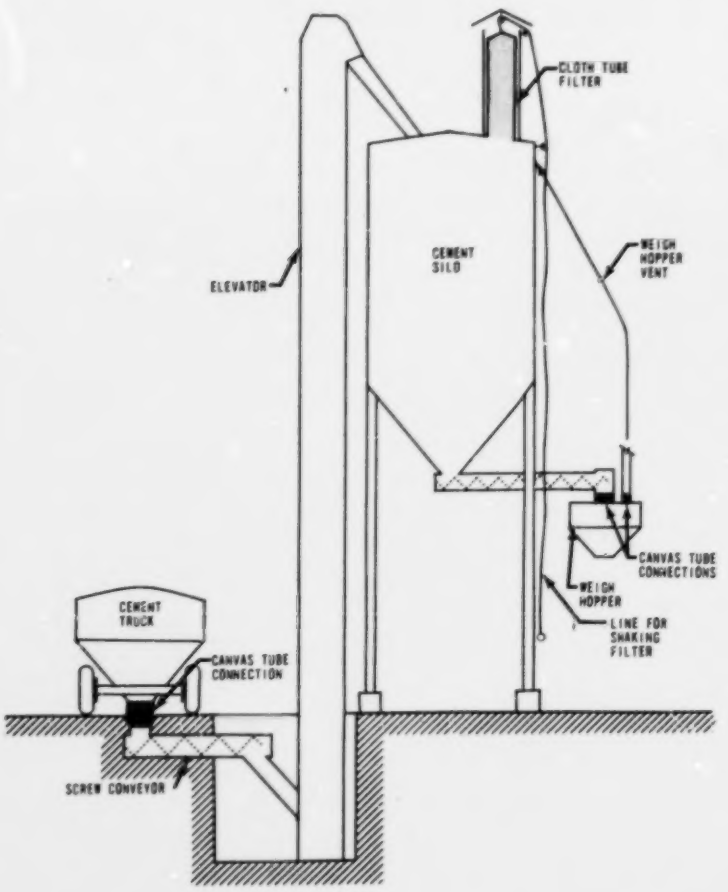


Figure 230. Cement-receiving and storage system.

advantage of using a bank of several simple filter vents as just described is the possibility of pressure build-up within the silo. If, for some reason, the filter should become blinded, there is danger of rupturing the silo. Therefore, proper maintenance and regular inspection of the filter are necessary.

Where baghouses are used to control other larger cement dust sources such as those existing in a dry-concrete-batching plant or in a central mix plant, then the cement silo can easily be vented to the same baghouse.

Cement weigh hopper

The cement weigh hopper may be a compartment in the aggregate weigh hopper or it may be a separate weigh hopper. Cement is usually delivered from the silo to the weigh hopper by an enclosed screw conveyor. To permit accurate weighing, a flexible connection between the screw conveyor and weigh hopper is necessary. A canvas shroud is usually used, and if properly installed and maintained, prevents dust emissions at this point. The weigh hopper is filled at a fairly rapid rate, and the displaced air entrains a significant amount of dust. This dust may be controlled by venting the displaced air back to the cement silo or by installing a filtered vent on the weigh hopper as described for cement silos.

The vent should be of adequate size to provide a filtering velocity of about 3 fpm, based upon the cement's volumetric filling rate. For example, if a weigh hopper is filled at the rate of 1,500 pounds in 1/2 minute, and the density of cement is 94 pounds per cubic foot, the displaced air rate equals 1,500/(94)(0.5), or 32 cfm. The required cloth area would then be 32/3 or 10.7 square feet.

Gathering hoppers

The dropping of a batch from the weigh hopper to the mixer can cause cement dust emissions from several points. In the loading of transit-mix trucks, a gathering hopper is usually used to control the flow of the materials. Dust can be emitted from the gathering hopper, the truck's receiving hopper, and the mixer. The design and location of the gathering hopper can do much to minimize dust emissions. The hopper should make a good fit with the truck receiving hopper, and its vertical position should be adjustable. Figure 231 illustrates a design that has been used successfully in minimizing dust emissions. Compressed-air cylinders raise and lower the gathering hopper to accommodate trucks of varying heights. A steel plate with a foam rubber backing is attached to the bottom of the gathering hopper and is lowered until it rests on the top of the truck's receiving hopper. Water for the mix is introduced through a jacket around the discharge spout of the gathering hopper and forms a dust-reducing curtain.

Discharge of the cement hopper into the center of the aggregate stream, and choke feed between the weigh hopper and the gathering hopper suppress dust emissions from the top of the gathering hopper.

DRY-CONCRETE-BATCHING PLANTS

Dry-concrete-batching plants are used in road construction work. Because of advances in freeway construction in recent years, plants such as these are located in metropolitan areas, often in residential zones. The plants are portable, that is, they must be designed to be moved easily from one location to another. This is, of course, a factor in the design of the air pollution control equipment.

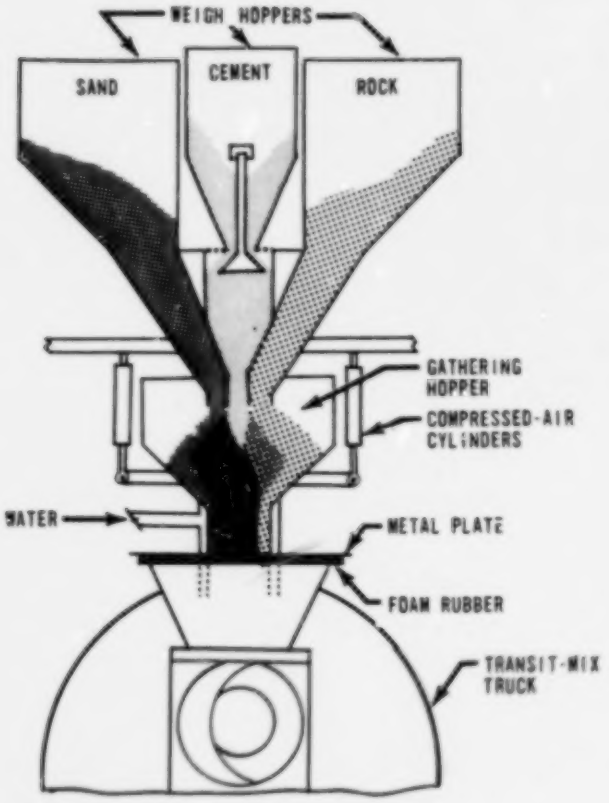


Figure 231. An adjustable gathering hopper.

The Air Pollution Problem

Dry batching poses a much more difficult dust control problem than wet batching does. Since most plants that do dry batching also do wet batching, the gathering hopper must be set high enough to accommodate transit-mix trucks. Since the receiving hopper of most transit-mix trucks is several feet higher than the top of the flat-bed trucks used in dry batching, there is a long free fall of material when a dry batch is dropped. This produces a considerable amount of dust, sufficient to violate most codes that have an opacity limitation applicable to this type of operation.

From an air pollution standpoint, the dust to be collected has characteristics similar to those of the cement dust already discussed for wet-concrete-batching plants. In dry batching, however, volumes of dust created are considerably greater because: (1) The amount of concrete batched is large, (2) no water is used, and (3) the batches are dropped rapidly into the waiting trucks to conserve time.

Hooding and Ventilation Requirements

A local exhaust system with an efficient dust collector is required to control a dry batching plant adequately. This is a difficult operation to hood without interfering with the truck's movement or the batch operator's view. The truck bed is usually divided into several compartments, a batch being dropped into each compartment. This necessitates repeated spotting of each truck under the direction of the batch operator; hence he must be able to see the truck at the drop point. A canopy-type hood just large enough to cover one compartment at a time provides effective dust pickup and affords adequate visibility. Figure 232 shows a closeup view of a hood of this type. The sides are made of sheets of heavy rubber to permit contact with the truck bed without damage. This hood is mounted on rails to permit it to be withdrawn to allow wet batching into transit-mix trucks.

The exhaust volume required to collect the dust varies with the shape and position of the hoods. With reasonably good hooding, the required volume is approximately 6,000 to 7,000 cfm.

Air Pollution Control Equipment

A baghouse is the most suitable type of dust collector for this service. Scrubbers have been used, but they have been plagued with difficulties such as low collection efficiency, plugged spray nozzles, corrosion, and waste-water disposal problems. A baghouse for this service should have a filtering velocity of 3 fpm. It may be of the intermittent shaking type, since sufficient opportunities for stopping the exhauster for bag shaking are usually available. Figure 233 is an overall view of a typically controlled dry batching plant with the baghouse shown on the left. The drop area tunnel is enclosed on the sides and partially on the ends.

Dust created by truck movement

In many instances the greatest source of dust from the operation of a concrete batch plant is that created by the trucks entering and leaving the plant area. If possible, the yard and access roads should be paved or oiled, or if this is not feasible, they should be watered frequently enough to suppress the dust.

CENTRAL MIX PLANTS

The central mix plant, as shown in Figure 234, is being used more and more extensively by the concrete industry in the Los Angeles area. In a central batch operation, concrete is mixed in a stationary mixer, discharged into a dump truck, and transported in a wet mixed condition to the pouring site.

The handling of aggregate and cement at these plants is similar to that at the other concrete batch plants.

Figure 232. Closeup of hood for controlling dry batching: (left) Hood in place, (right) hood in retracted position (Graham Bros., El Monte, Calif.).

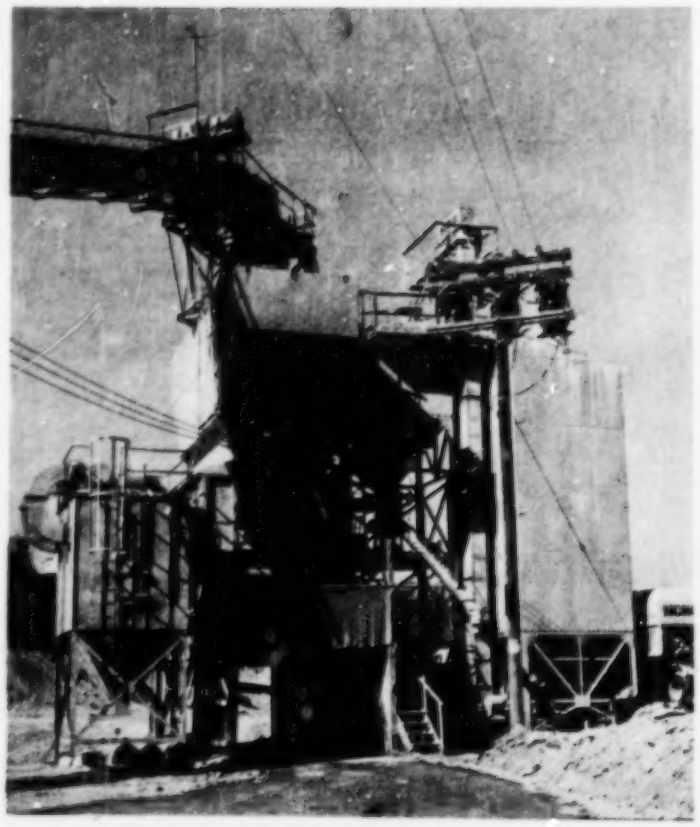


Figure 233. Overall view of wet- and dry-concrete-batching plant and baghouse located at a California Freeway project (Guy F. Atkinson Co., Long Beach, Calif.).

Sand, aggregate, cement, and water are all weighed or metered as in a wet-concrete-batching plant and discharged through an enclosed system into the mixer.

Figure 234. Overall view of a central mix concrete-batching plant controlled by a baghouse (Griffith Co., Los Angeles, Calif.).

The Air Pollution Problem

From an air pollution control standpoint, this type of operation is preferable to dry batching. The dust is more easily captured at the batch plant, and further, there is no generation of dust at the pouring site. The operation is also preferable to wet batching because designing control equipment for a stationary mixer is easier than it is for a transit-mix truck-loading area.

Hooding and Ventilation Requirements

Effective control at the discharge end of the mixer is a function of good hood design and adequate ventilation air. A hydraulically operated, swing-away, cone-shaped hood, as shown in Figure 235, is normally used with a 2-inch clearance between the hood and the mixer. This installation employs a mixer with a capacity of 8 cubic yards. The discharge opening of the mixer is 40 inches in diameter. Ventilation air was found to be 2,500 cfm. For a hood of this type, indraft face velocities should be between 1,000 and 1,500 fpm. Velocities such as these are required for handling the air discharged from the mixer, which is displaced air and inspirated air from the aggregate and cement falling into the mixer.

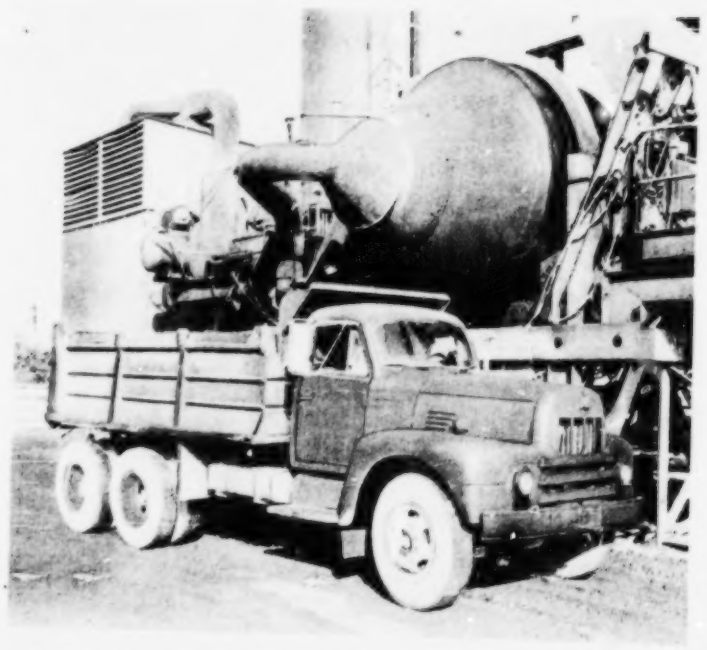


Figure 235. Hood for central mix plant: (top) In retracted position, (bottom) in closed position (Griffith Co., Los Angeles, Calif.).

Air Pollution Control Equipment

A baghouse, such as is shown in Figure 235, is required to collect the dust emissions. A filtering velocity of 3 fpm is adequate. Other baghouse features are similar to those previously discussed for dry-concrete-batching plants.

CEMENT-HANDLING EQUIPMENT

Equipment used in handling cement includes hoppers, bins, screw conveyors, elevators, and pneumatic conveying equipment. The equipment to be discussed in this section is that involved in the operation of a bulk cement plant, which receives, stores, transships, or bags cement. Its main purpose is usually to transfer cement from one type of carrier to another, such as from railway cars to trucks or ships.

THE AIR POLLUTION PROBLEM

In the handling of cement, a dust problem can occur if the proper equipment or hooding is not used. A well-designed system should create little air pollution. Sources of emissions include the storage and receiving bins, elevators, screw conveyors, and the mobile conveyances.

Characteristics of cement dust have been discussed in the section on wet-concrete-batching plants.

HOODING AND VENTILATION REQUIREMENTS

Receiving Hoppers

Railway cars are usually unloaded into an underground hopper similar to the one described for trucks in the preceding section. The canvas tube is usually, however, permanently attached to the receiving hopper and is attached by a flange to the discharge spout of the hopper car. When flanges fit properly, emissions from equipment such as this are usually negligible.

Storage and Receiving Bins

Bins filled by bucket elevators must be ventilated at a rate equal to the maximum volumetric filling rate plus 200 fpm indraft at all openings. The area of openings is usually very small. Since most bulk

plants have a number of bins, a regular exhaust system with a dust collector provides a more practical solution than the silo filter vents do that were described for concrete batch plants. Bins filled by pneumatic conveyors must, of course, use a dust collector to filter the conveying air. Gravity-fed bins and bins filled by bucket elevators can use individual filter vents if desired.

Elevators and Screw Conveyors

Bucket elevators used for cement service are always totally enclosed. Ventilation must be provided for the bin into which it discharges. Since elevators are nearly always fed by a screw conveyor that makes a dust-tight fit at the feed end, no additional ventilation is usually required. Another type of conveyor used for cement service is a vertical screw conveyor. These, of course, cause no dust emissions as long as they have no leaks. Horizontal screw conveyors are frequently fed or discharged through canvas tubes or shrouds. These must be checked regularly for tears or leaks.

Hopper Truck and Car Loading

Hopper trucks and railroad cars are usually filled from overhead bins and silos. The amount of dust emitted is sufficient to cause a nuisance in almost any location. Figure 236 shows a type of hood and loading spout that permits these emissions to be collected with a minimum amount of air. The ventilation rate is the same as for bins, the displaced air rate plus 200 fpm through all openings. If the hood is designed to make a close fit with the hatch opening, the open spaces are very small and the required exhaust volume is small. The hood is attached to the telescoping cement discharge spout in such a way that it can be raised and lowered when hopper trucks are changed.

AIR POLLUTION CONTROL EQUIPMENT

A baghouse has been found to be the most satisfactory dust collector for handling the ventilation points described. All sources are normally ducted to a single baghouse. Cotton sateen cloth with a filtering velocity of 3 fpm is adequate. Dacron cloth, which provides longer wearing qualities but is more expensive, can also be used.

ROCK AND GRAVEL AGGREGATE PLANTS

Rock and gravel plants supply sand and variously sized aggregates for the construction and paving industries. The sources of most aggregates used in Los Angeles County are the gravel beds in the San Fernando and San Gabriel valleys. The processing of the gravel consists of screening out the usable sizes and crushing the oversize into various size ranges. A simplified flow diagram for a typical plant is shown in Figure 237. Incoming material is routed through a jaw crusher, which is set to act upon rocks larger than about 6 inches and to pass smaller sizes. The product from this crusher is screened into sizes smaller and larger than 1-1/2 to 2 inches, the undersize going to a screening plant, and the oversize to the crushing plant. These next crushers are of the cone or gyratory type, as shown in Figure 238. In a large plant, two or three primary crushers are used in parallel followed by two to five secondary crushers in parallel.

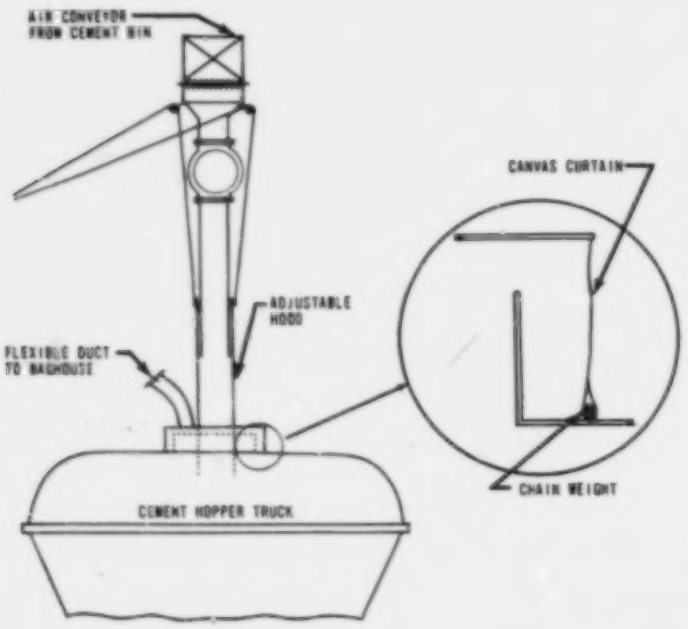


Figure 236. Hood for truck-loading station.

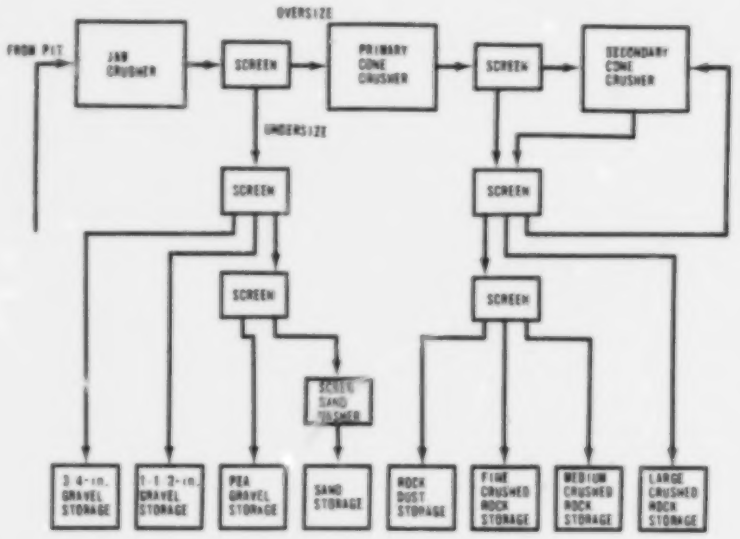


Figure 237. Simplified flow diagram of a typical rock gravel plant.

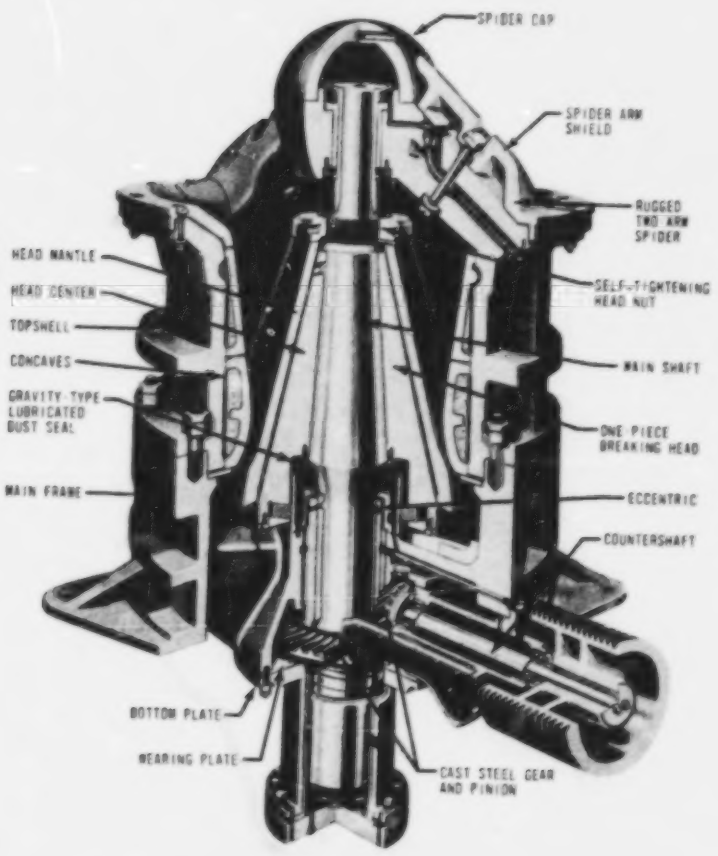


Figure 238. Gyratory crusher (Allis-Chalmers Manufacturing Company, Milwaukee, Wis.).

THE AIR POLLUTION PROBLEM

The sand and rock, as it comes from the pit, is usually moist enough to remain nondusting throughout the sand- and uncrushed-rock-screening stages. When the pit material is not sufficiently moist, it must be wetted before it leaves the pit. As the larger rocks are crushed, dry surfaces are exposed and airborne dust can be created.

An inventory of sources of dust emissions usually begins with the first crusher and continues with the conveyor transfer points to and including the succeeding crushers. Here the rock is more finely ground, and dust emissions become greater. As the process continues, dust emissions are again prevalent from sources at conveyor transfer points and at the final screens.

HOODING AND VENTILATION REQUIREMENTS

The points that require hooding and ventilation are the crusher discharge points, all elevator and belt conveyor transfer points, and all screens.

All these dust sources should be enclosed as nearly completely as possible and a minimum indraft velocity of 200 fpm should be maintained through all open areas. The following rules are also a guide to the amount of ventilation air required (Committee on Industrial Ventilation, 1960):

1. Conveyor transfer points--350 cfm per foot of belt width for speeds of less than 200 fpm; 500 cfm per foot of belt width for belt speeds over 200 fpm;

2. bucket elevators--tight casing required with a ventilation rate of 100 cfm per square foot of casing cross section;

3. vibrating screens--50 cfm per square foot of screen area, no increase for multiple decks.

AIR POLLUTION CONTROL EQUIPMENT

One method of suppressing the dust emissions consists of using water to keep the materials moist at all stages of processing; the other, of using a local exhaust system and a dust collector to collect the dust from all sources.

If the use of water can be tolerated, then water can be added with spray nozzles, usually at the crusher locations and the shaker screens. Figure 239 shows nozzle arrangements for control of emissions from the outlet of the crushers, Figure 240, nozzle arrangements at the inlet to the shaker screens. The amount of water to be used can best be determined by trial under normal operating conditions. Water quantities vary with crusher size, crusher setting, feed rate, type of feed, and initial moisture content of the feed.

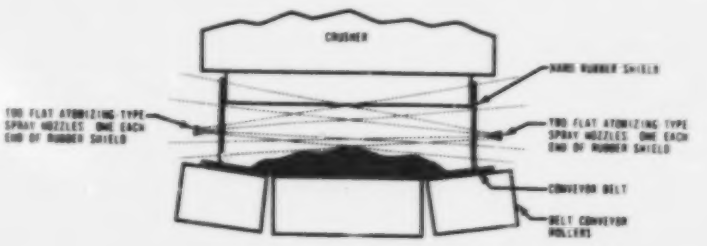


Figure 239. Nozzle arrangement for control of dust emissions upon discharge of crusher.

Adding water in the described manner tends to cause blinding of the finest size screens used in the screening plants, which thereby reduces their capacity. It also greatly reduces the amount of rock dust that can be recovered, since most of the finest particles adhere to larger particles. Since rock dust is in considerable demand, some operators prefer to keep the crushed material dry and collect the airborne dust with a local exhaust system.

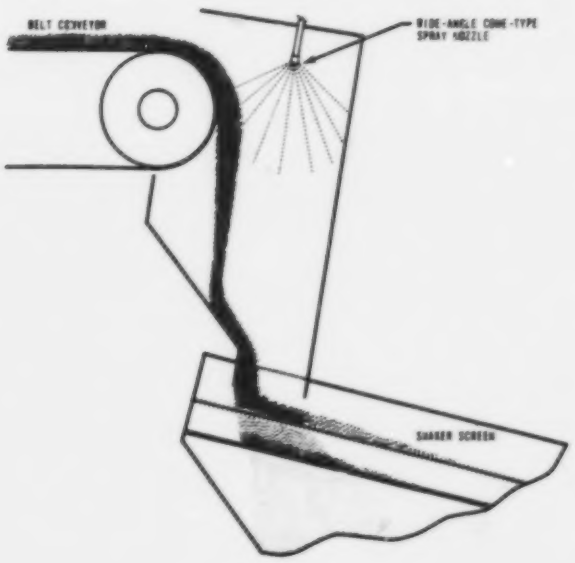


Figure 240. Nozzle arrangement for control of dust emissions from the inlet to the shaker screens.

The preferred dust collector device is a baghouse. Standard cotton sateen bags can be used at a filtering velocity of 3 fpm. For large plants that maintain continuous operation, compartmented collectors are required to allow for bag shaking. Most plants, however, have shutdown periods of sufficient frequency to allow the use of a noncompartmented collector. Virtually 100 percent collection can be achieved, and as mentioned previously, the dust is a salable product.

A combination of a dry centrifugal collector and a wet scrubber is sometimes used. In this case, only the centrifugal device collects material in a salable form. A centrifugal collector alone would allow a considerable amount of very fine dust to be emitted to the atmosphere. A scrubber of good design is required, therefore, to prevent such emissions.

MINERAL WOOL FURNACES

INTRODUCTION

The general product classification known as mineral wool was formerly divided into three categories: Slag wool, rock wool, and glass wool.

Slag wool, which was made from iron slag or copper slag, was first successfully manufactured in England in 1885, after earlier attempts had failed in the United States (Kirk and Othmer, 1947). The first manufacture of rock wool (which was made from natural rock) took place at Alexandria, Indiana, in 1897. Glass wool (made from glass cullet or high silica sand, or both) was later pioneered in Newark, Ohio, in 1931.

Today, however, straight slag wool and rock wool as such are no longer manufactured. A combination of slag and rock constitutes the cupola charge materials in more recent times, yielding a product generally classified as mineral wool, as contrasted with glass wool.

Mineral wool is made today in Los Angeles County with a cupola by using blast furnace slag, silica rock, and coke (to serve as fuel). It has been produced here in the past by using a reverberatory furnace charged with Borax ore tailings, dolomite, and lime rock heated with natural gas.

Types and Uses of Mineral Wool Products

Mineral wool consists of silicate fibers 5 to 7 microns in diameter (Allen et al., 1952) and about 1/2-inch long, and is used mainly for thermal and acoustical insulation. It has a density of about 6 pounds per cubic foot and is collected initially as a continuous loose blanket of fibers on a conveying belt. It is sold, however, as quilt, loose rolls, industrial felt, batts, or in a granulated form.

Batts are rectangular sections of mineral wool approximately 4 by 15 by 48 to 60 inches in size. These sections are covered on top and two sides with paper, and the bottom is covered with either an asphalt-coated paper or aluminum foil. Batts are used for thermal insulation in residential homes and for many other insulation needs.

Granulated mineral wool, which is handled pneumatically, is also used for home insulation. Quilt is normally 60 inches wide and 2 inches thick and contains the binder agent and paper cover. It is used primarily for industrial insulation. Loose rolls, which contain no binder agent and are sometimes enclosed in a fine mesh cover, are used for applications such as water heaters and house trailers. Industrial felt consists of wool blanket with binder agent but without a paper covering and has a slightly greater density than that of batts. It is used for items such as walk-in refrigerators and industrial ovens.

Mineral Wool Production

The cupola or furnace charge is heated to the molten state at about 3,000°F, after which it is fed by gravity into a device at the receiving end of a large blowchamber. This device may be a trough-like arrangement with several drains, or a cup-like receiver on the end of a revolving arm. The molten material is atomized by steam and blasted horizontally towards the other end of the blowchamber. When the cup or spinner device is used, the action of the steam is assisted by centrifugal force. The steam atomizes the molten rock into small globules that develop and trail long, fibrous tails as they

travel towards the other end of the blowchamber. These fibers reportedly can be drawn mechanically or spun without steam, but this process is foreign to Los Angeles County.

Phenolic resin or a mixture of linseed oil and asphalt are examples of binding agents that can be atomized at the center of the steam ring by a separate steam jet to act as a binder for the fibers. Annealing oil can also be steam atomized near the steam ring to incorporate a quality of resilience to the fibers that prevents breakage.

A temperature between 150° and 250°F is maintained in the blowchamber. Blowers, which take suction beneath the wire mesh conveyor belt in the blowchamber, aid the fibers in settling on the belt. The mineral wool blanket of fibers is conveyed to an oven for curing the binding agent. Normally gas fired, the oven has a temperature of 300° to 500°F.

The mineral wool is next programmed through a cooler, as shown in the flow diagram in Figure 241. Usually consisting of an enclosure housing a blower, the cooler reduces the temperature of the blanket to prevent the asphalt, which is applied later to the paper cover, from melting.

To make batts, the blanket leaving the cooler is processed through a multibladed, longitudinal cutter to separate it into sections of desired widths. Brown paper and either asphalt-coated paper or aluminum foil are then applied to the sections of blanket. The asphalt-coated paper is passed through a bath of hot asphalt just before its application to the underside of each section. This asphalt film serves as a moisture barrier as well as a bonding agent against walls. The paper-covered sections are cut to desired lengths by a transverse saw, after which the finished product is packed for storage and shipment. The two cutters, paper and asphalt applicators, and conveyor systems are sometimes referred to collectively as a batt machine.

A granulated-wool production line differs from that just described in that the mineral wool blanket, after leaving the blowchamber, is fed to a shredder for granulation, then to a pelletizer. The pelletizer serves two functions, namely, to form small 1-inch-diameter wool pellets and to drop out small black particles called shot, which form as the molten slag cools in the blowchamber. A bagging operation completes the process. Since no binding agent is required, the curing oven is eliminated.

THE AIR POLLUTION PROBLEM

The major source of emissions is the cupola or furnace stack. Its discharge consists primarily of condensed fumes that have volatilized from the

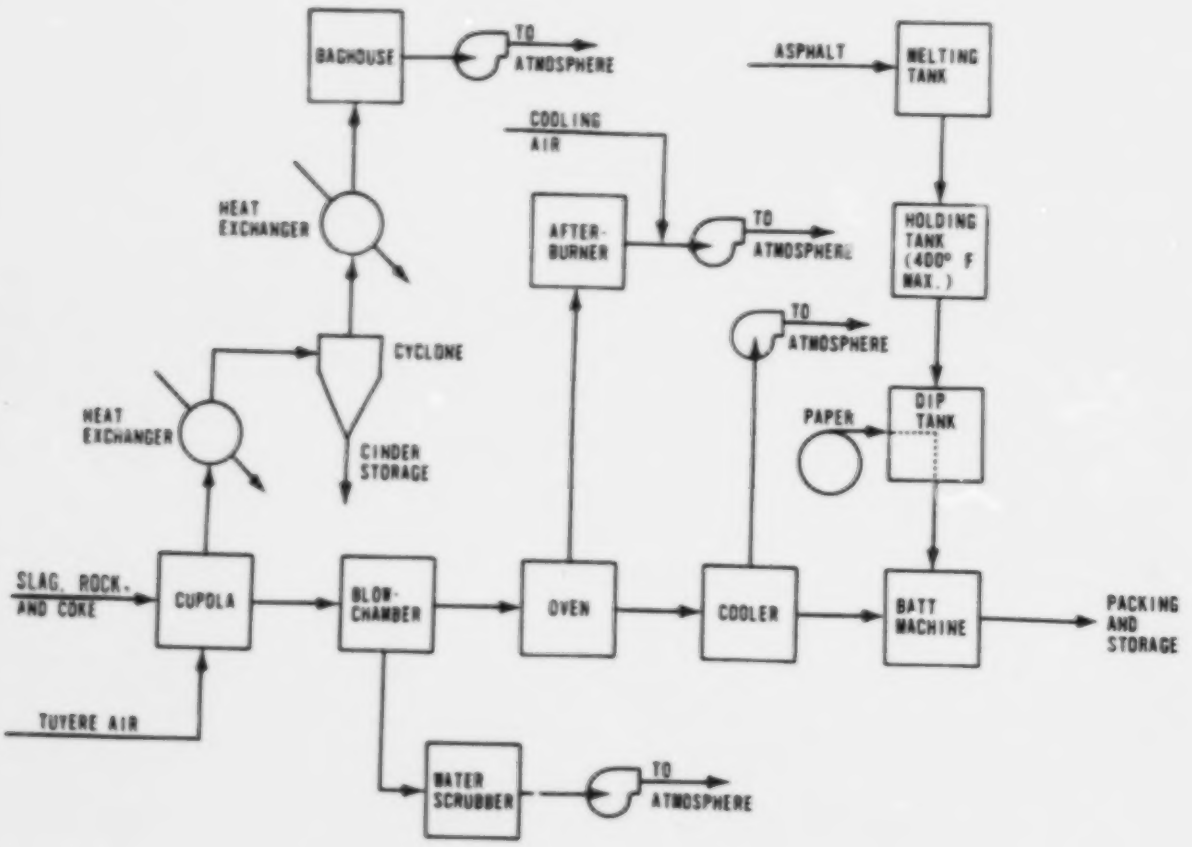


Figure 241. Flow diagram of mineral wool process.

molten charge, and gases such as sulfur oxides and fluorides. Amounting to as much as 100 pounds per hour and submicron in size, condensed fumes create a considerable amount of visible emissions and can be a public nuisance. Table 98 shows the weights of emissions discharged from uncontrolled cupolas and furnaces. A particle size distribution of the emissions is shown in Table 99.

Another source of air pollution is the blowchamber. Its emissions (see Table 100) consist of fumes, oil vapors, binding agent aerosols, and wool fibers. In terms of weight, a blowchamber may also emit as much as 100 pounds of particulate matter per hour at a production rate of 2 tons per hour if the blowchamber vent is uncontrolled. Approximately 90 percent of these emissions consists of mineral wool fibers.

Types of air contaminants from the curing oven are identical to those from the blowchamber except that no metallurgical fumes are involved. These emissions amount to approximately 8 pounds per hour at a production rate of 2 tons per hour, as seen in Table 101, since the amount of wool fibers discharged is much less than that for a blowchamber. From a visible standpoint, however, these pollutants may create opacities as high as 70 percent. Emissions from the cooler are only 4 or 5 pounds per hour at a production rate of 2 tons per hour (see Table 102). The asphalt applicator can also be a source of air pollution if the temperature of the melting or holding pot exceeds 400°F.

HOODING AND VENTILATION REQUIREMENTS

No special hooding arrangements as such are required in any of the exhaust systems employed in the control of pollution from mineral wool processes. The one possible exception is that canopy hoods may be used over the asphalt tanks if the emissions from these tanks are excessive and are vented to an air pollution control device.

The ventilation requirements for the various individual processes in a mineral wool system are categorized as follows:

1. Cupolas. Based on test data, exhaust requirements can be estimated to be 5,000 to 7,000 scfm for a cupola with a process weight of from 4,000 to 4,500 pounds per hour, on the assumption that no outside cooling air is introduced. The charge door should be kept in the closed position to obtain maximum benefit from the capacity of the exhaust fan. A barometric damper in the line between the cupola and the blower can be used to control the amount of gases pulled from the cupola. The objective is to remove all tuyere air plus an additional amount of air to maintain a slight negative pressure above the burden.

2. Reverberatory furnaces. Ventilation requirements are about 15,000 to 20,000 cfm (at 600°F) for a furnace sized to produce 1,500 to 3,000 pounds of mineral wool per hour. The heat in these furnace gases can be used in making steam before filtration.

3. Blowchambers. For a blowchamber with a size of about 4,500 cubic feet and with a capacity for processing 4,000 pounds of wool an hour, the minimum ventilation requirements are 20,000 to 25,000 scfm. All duct takeoffs must be located at the bottom of the blowchamber beneath the conveyor to create downdraft,

Table 98. DUST AND FUME DISCHARGES FROM MINERAL WOOL CUPOLAS AND FURNACES

Test data	Test No.				
	Cupola				Reverberatory furnace
	1	3	6A	13	19[a]
Process wt, lb/hr	3,525	4,429	-	3,625	3,050
Stack volume, scfm	4,550	4,545	4,510	4,760	2,740
Stack gas temp, °F[b]	309	295	314	338	625
Stack emissions, lb/hr	49.7	45.6	51.1	29.0	7.3
gr/scf	1.28	0.21	1.33	0.71	0.31
SO_2, mg/scf	32.6	-	-	-	-
Total SO_2, %	0.04	-	-	-	-
SO_3, mg/scf	18.5	-	-	-	-
CO, %	0.9	-	-	-	-

[a]An estimated 75 percent of the furnace gases was used for waste heat purposes and was not, therefore, included in the test.
[b]As measured after cooling, just upstream from control device.

which packs the newly formed wool fibers onto the conveyor. From this viewpoint, 35,000 scfm would be more desirable. In addition, this increased ventilation holds the blowchamber temperature down to tolerable limits, which determine the type of air pollution control equipment to be selected. If the plant is processing granulated wool instead of batts, downdraft is less important and satisfactory operation can be achieved with a 25,000-scfm exhaust system. If a lint cage is used to trap wool fibers in the discharge gases, frequent cleaning (four times an hour) of the cage is imperative for proper ventilation.

Table 99. PARTICLE SIZE ANALYSIS BY MICROSCOPE OF TWO SAMPLES TAKEN FROM THE DISCHARGE OF A MINERAL WOOL CUPOLA FURNACE

Test No. 9A			
Size range, μ	Total count	Percent by number	Percent by wt
45 to 75	10	0.5	75.0
15 to 45	10	0.5	10.0
7.5 to 15	40	2.0	14.5
1 to 7.5	100	5.0	0.5
1	2,000	92.0	Nil
Tyler screen analysis: Retained on 200 mesh (74 μ): 33.8%			
Retained on 325 mesh (44 μ): 20.3%			
Ignition loss: 10% Retained on pan (44 μ): 49.9%			

Test No. 9B			
Average particle size, μ	Total count	Percent by number	Percent by wt
200	2	0.1	85.0
60	8	0.4	9.5
40	10	0.5	3.5
10	20	1.0	1.08
5	100	5.0	0.07
1	930	93.0	Nil

4. Curing ovens. Exhaust requirements for a 2,500-cubic-foot oven operating at 300° to 500°F and capable of processing 4,000 to 6,000 pounds of mineral wool an hour are about 5,000 scfm. Sufficient oven gases must be removed to prevent a pressure buildup so that leakage does not occur. In sizing the fan, consideration must be given to temperature rises and possibly also to the introduction of outside cooling air for proper fan operation, particularly if the oven discharge gases are incinerated.

5. Coolers. Coolers normally do not require air pollution control devices. If outside ambient air is used as the cooling medium, the ventilation requirements are 10,000 to 20,000 cfm for a cooler whose area is about 70 square feet.

6. Asphalt tanks. If temperature regulators are successfully used to control emissions, the ventilation requirements for melting, holding, and dip tanks will be about 75 cfm for each square foot of surface area. This value is for open tanks and for hoods having one open side. If the melting and holding tanks are closed, natural-draft stacks may be used.

Table 100. EMISSIONS FROM MINERAL WOOL BLOWCHAMBERS

	Test No.					
	1	6C	13	14	17	25
Process wt, lb/hr	3,525	-	3,625	3,525	3,700	4,120
Stack volume, scfm	11,100	17,200	15,760	28,728	19,750	15,400
Stack gas temp, °F	196	196	160	188	167	200
Blowchamber emissions, lb/hr	9.20	5.02	7.11	98.21	-	8.3
Type of control equipment	None	a	None	None	Lint cage	Two wet centrifugal water scrubbers in parallel
Dust concentration, gr/scf						
Inlet	0.097	0.034	0.0526	0.399	-	0.063
Outlet	0.097	0.011	0.0526	0.399	0.012	0.028
Dust emissions, lb/hr						
Inlet	9.20	5.02	7.11	98.21	-	8.30
Outlet	9.20	1.62	7.11	98.21	2.03	3.60
Control efficiency, %	-	67.90	-	-	-	57
SO_2, mg/scf	1.04	-	-	-	-	-
Total SO_2, %	0.0013	-	-	-	-	-
Aldehydes, mg/scf	1.03	-	-	-	-	-
Total aldehydes, %	0.0036	-	-	-	-	-
Combustibles, %	-	-	-	-	-	-

[a] This control equipment consisted of a water scrubber followed in series by an electrical precipitator.

Table 101. EMISSIONS FROM MINERAL WOOL CURING OVENS

	Test No.					
	1	6E	13	18[a]	22	24
Process wt, lb/hr	3,525	-	3,625	3,050	5,180	3,500
Stack volume, scfm	4,740	6,130	4,862	1,642	8,000	4,870
Stack gas temp, °F	326	314	353	310	200	270
Oven emissions, lb/hr	8.95	22.30	5.20	2.27	15.20	5
Type of control equipment	None	b	None	None	Catalytic afterburner	Direct-flame afterburner
Dust concentration, gr/scf						
Inlet	0.22	0.42	0.125	0.161	0.221	0.119
Outlet	0.22	0.083	0.125	0.161	0.071	0.032
Dust emissions, lb/hr						
Inlet	8.95	22.30	5.20	2.27	15.20	5
Outlet	8.95	4.36	5.20	2.27	4.90	2.50
Control efficiency, %	-	81	-	-	68	50
SO_2, mg/scf	3.23	-	-	-	-	-
Total SO_2, %	0.0053	-	-	-	-	-
Aldehydes, mg/scf	1.24	-	-	-	-	-
Total aldehydes, lb/hr						
Inlet	-	-	-	-	1.90	2.20
Outlet	-	-	-	-	0.90	0.94
NO_2, lb/hr						
Inlet	-	-	-	-	0.60	0.15
Outlet	-	-	-	-	0.70	0.45
Afterburner temp, °F	-	-	-	-	840	1,230

[a]During this test the oven was heated with waste heat from a reverberatory furnace. The quantity of dust emissions appears low as a result of considerable leakage at the oven. Of the particulates collected, 95.4% were volatile or combustibles.

[b]This control equipment consisted of a water scrubber followed in series by an electrical precipitator.

Table 102. EMISSIONS FROM MINERAL WOOL COOLERS

	Test No.			
	1	17	18	19
Process wt, lb/hr	3,525	3,700	3,050	3,050
Stack volume, scfm	1,850	8,500	16,696	8,980
Stack gas temp, °F	128	273	170	288
Cooler emissions, lb/hr	0.75	2.55	3.58	8.39
gr/scf	0.047	0.035	0.025	0.109
SO_2, mg/scf	0.49	-	-	-
Total SO_2, %	0.0006	-	-	-
Aldehydes, mg/scf	0.304	-	-	-
Total aldehydes, %	0.0009	-	-	-

AIR POLLUTION CONTROL EQUIPMENT

Baghouse Collection and Cupola Air Contaminants

Baghouses have proved to be an effective and reliable means of controlling the discharge from mineral wool cupolas. An installation of this type is shown in Figure 242. Dacron or Orlon bags, which can withstand temperatures up to 275°F, should be used. Of these two synthetic fabrics, Dacron is now the more common, and features several advantages over Orlon, as discussed in Chapter 4. Glass fabric bags cannot be used, owing to the fluorides in the cupola effluent. (Results of a stack test disclose fluorides in a concentration 9.85 percent by weight in the particulate matter discharged from a cupola. The life of glass bags under these conditions is about 1 week.)

Provisions for automatic bag shaking should be included in the baghouse design. Sufficient cloth area should be provided so that the filtering velocity does not exceed 2.5 fpm.

Since the discharge temperature of the gas is about 1,000°F, heat-removing equipment must be used to prevent damage to the cloth bags. This can be accomplished with heat exchangers, evaporative coolers, radiant cooling columns, or by dilution with ambient air. The cooling device should not permit the temperature in the baghouse to fall below the dewpoint. Safety devices should be included to divert the gas stream and thus protect the baghouse from serious damage in the event of failure of the cooling system. In some instances it may also be desirable to include a cyclone or knockout trap someplace upstream of the baghouse to remove large chunks of hot metal that can burn holes in the bags even after passing through the cooling system.

The solution to a typical design problem involving a baghouse and an evaporative cooling system serving a cupola is described in Chapter 6.

Baghouses should be equally effective in controlling emissions from reverberatory furnaces. The comments made about cupolas are generally applicable to these furnaces. Excelsior-packed water scrubbers have been tried in Los Angeles County but did not comply with air pollution statutes relating to opacity limitations.

Afterburner Control of Curing Oven Air Contaminants

The effluent from the curing oven is composed chiefly of oil and binder particles. These emissions, while not a great contributor to air pollution in terms of weight, are severe in terms of opacity. Since they are combustible, a possible method of control is incineration. This method, in fact, has proved practical for the mineral wool plant.

Generally, afterburners are divided into two categories, depending upon the method of oxidation. These are direct-flame and catalytic. Important considerations for the direct-flame type (see Table 103) are flame contact, residence times, and temperature. The afterburner should be designed so that a maximum of mixing is obtained with the flame. The design should also provide sufficiently low gas stream velocities to achieve a minimum retention time of 0.3 second. An operating temperature of 1,200°F is the minimum requirement for efficient incineration. Figure 243 shows the effectiveness of the direct-flame type on curing oven emissions at different operating temperatures.

Table 103. DATA FOR A MINERAL WOOL CURING OVEN CONTROLLED BY A DIRECT-FLAME AFTERBURNER

Oven data
Type, gas fired, conveyorized
Operating temp, 350° to 450°F
Heat input, 4 million Btu/hr
Afterburner data
Type, direct flame, gas fired, two-pass
Flame contact device, deflector plate
Heat input, 5 million Btu/hr
Size, 4 ft dia x 9 ft length with 3 ft dia x 10 ft length Insulated retention tube
Gas temp inlet, 270°F
Operating temp, 1,240°F
Gas velocity, 37 ft/sec
Retention time, 0.3 sec
Collection efficiency (at 1,230°F)
On particulate matter, 50%
On aldehydes, 59%
On combustibles, 52%
On solvent soluble material, 68%

If a catalytic afterburner is used, the gas stream must be preheated to about 1,000°F. Some type of precleaner must be used to remove the mineral wool fibers and thus prevent fouling of the catalytic elements. Because of this problem, catalytic afterburners have not proved very satisfactory for this service.

Table 101 reflects a comparison of the effectiveness of both afterburner types as a control device on mineral wool curing ovens. Electrical precipitators have been used as an alternative means of controlling emissions from mineral wool curing ovens. The precipitator is, however, preceded by a water scrubber and high-velocity filter to remove the gummy material that would normally foul the ionizer and plate sections.

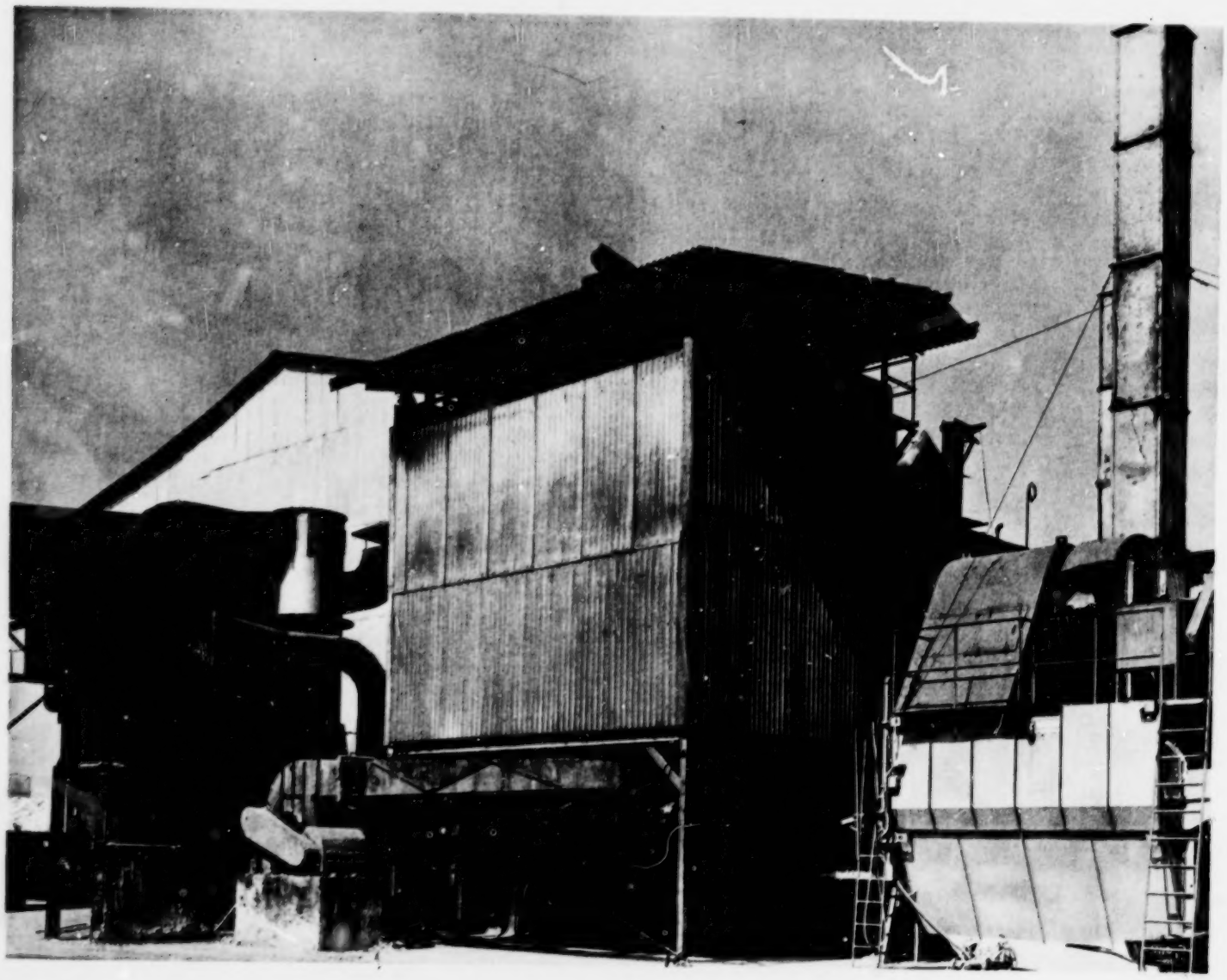


Figure 242. Baghouse controlling a mineral wool cupola.

Heat exchanger data:

No. 1	No. 2
Tube side, gas	Tube side, gas
No. passes, 1	No. passes, 1
Shell side, cooling air	Shell side, cooling air
No. passes, 4	No. passes, 3
Air vol, 2,840 scfm	Air vol, 10,500 cfm
Tube surface, 895 ft^2	Tube surface, 1,740 ft^2
Inlet temp (gas), 650°F	Inlet temp (gas), 400°F
Outlet temp (gas), 440°F	Outlet temp (gas), 275°F

Baghouse data:

Type, pullthrough, tubular	Tube size, 11½ in. dia x 15½ ft length
Filter medium, orlon	Gas temp inlet, 250°F
Filter area, 5,232 ft^2	Collection efficiency, 97%
Shaking cycle, 30 minutes (Automatic, staggered by compartment)	

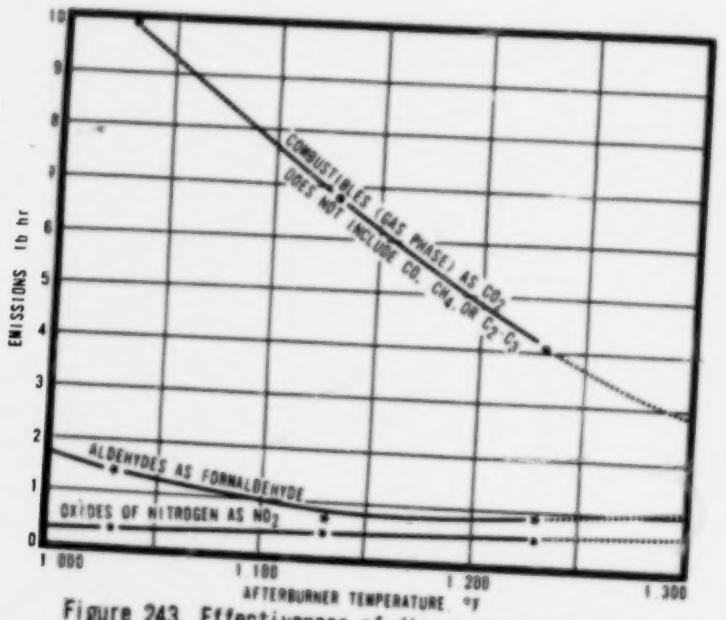


Figure 243. Effectiveness of direct-flame afterburner on curing oven emissions as a function of afterburner temperature.

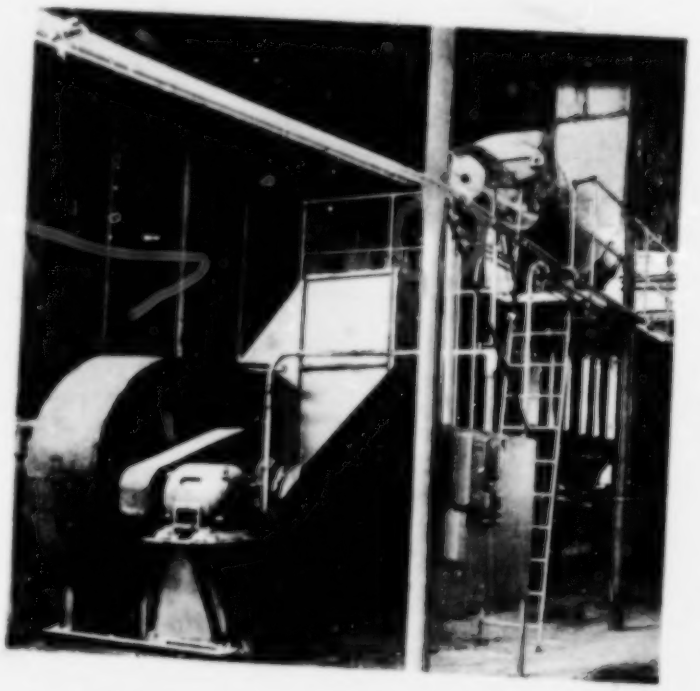


Figure 244. Mineral wool blowchamber controlled by an inertial-type water scrubber.

Reducing Blowchamber Emissions

If the blowchamber's temperature is maintained below 175°F to preclude the formation of oil mist, then the major air pollution problem is posed by wool fibers. The most practical means of collecting these fibers is an efficient water scrubber, as shown in Figure 244. If, however, the blowchamber's temperature rises above 250°F, the feasibility of using a water scrubber is diminished. Test 25 shown in Table 100 gives the results of a stack analysis of two wet centrifugal water scrubbers placed in parallel and venting a blowchamber. A deflector plate at the blowchamber's entrance can be used to deflect a large portion of the molten shot and thereby reduce the blowchamber's temperature as well as reduce the chance for contact with oil mists. Water injection at the receiving end of the blowchamber combined with adequate ventilation air can further reduce this temperature to 150°F or less.

A simple wire-mesh lint cage collects as much as 90 pounds of large pieces of fibrous material per hour. Constant cleaning of the lint cage is, however, required; otherwise lack of ventilation results in a temperature rise in the blowchamber.

Large water content in the blowchamber effluent precludes classifying the baghouse as a practical control device for the blowchamber. In addition, the resin binder would plug the pores of the bags, resulting in a severe maintenance problem.

Controlling Asphalt Fumes

Asphalt vapors emitted by the asphalt applicator can become a serious source of air pollution if the asphalt's temperature is permitted to exceed 400°F. The simplest and most economical method of reducing these emissions to the atmosphere is to control the temperature. The temperature can sometimes be held to a maximum of 325°F by proper asphalt selection, thermostatic control, and use of a holding pot separate from the melting pot. (Asphalts made from different crude oils have different vaporizing points.)

If temperature control is used, best results can be obtained by using three separate tanks: Melting tank, holding tank, and dip tank. All three should be provided with individual heating facilities, which thereby permits minimum temperature differentials between tanks. In this manner, the holding tank's temperature can be held to a minimum (about 400°F) without regard to heat loss at the dip tank. Automatic temperature controls are necessary for the holding tank. An asphalt feed control bar installed on the asphalt roller in the dip tank permits the temperature to be reduced even further. This feed control bar, which is adjustable against the roller, controls the thickness of the asphalt film applied to the paper; otherwise this thickness would have to be controlled by controlling temperature and asphalt viscosity.

If control of asphalt temperature proves impractical, then a collection device should be used to prevent the fumes from escaping to the atmosphere. This can be done effectively with a two-stage, low-voltage electrical precipitator, and sometimes with a high-efficiency water scrubber. If a scrubber

is used, recirculation of the water is not advised, since plugging of the water nozzles may occur unless the asphalt particles are somehow removed, say by flotation.

PERLITE-EXPANDING FURNACES

INTRODUCTION

Perlite is a glassy, volcanic rock of the composition of obsidian but divided into small, spherical bodies by the tension developed during its contraction on cooling. It is grayish with a soft, pearly luster. Chemically, perlite consists chiefly of the oxides of silicon and aluminum combined as a natural glass with water of hydration. Upon rapid heating, the escaping water of hydration causes the spherules to expand and form white, cellular, low-density particles. This process is termed exfoliation.

Uses

About 90 percent of expanded perlite is used as an aggregate in plaster and concrete. When mixed with gypsum and water, perlite creates a plaster that can be troweled or sprayed on lath to form a lightweight, resilient wall or ceiling. Perlite insulating concrete can be used in the form of precast slabs or poured on lath, formboard, or steel decking. Loose perlite is also used extensively as an insulating fill for concrete block walls, as a cavity wall insulation, and as an insulating fill in attic floors. Other uses for perlite include: Oil well cement; mineral filter aid; pipe, furnace, and boiler insulation; foundry sand additive; packaging medium; soil conditioner; and ceramic and paint additive.

Mining Sites

Several perlite ore deposits are in California, and other deposits are in six of the Rocky Mountain States. Perlite ore is surface mined or quarried and is normally dried, crushed, and screened at the mine. The normal size of crude perlite for plaster aggregate ranges from minus 12 or 14 mesh to plus 40 or 60 mesh. Some plants use a size range with no limitations on the fines. Crude perlite for concrete aggregate ranges from 1/8 inch, plus 16 mesh, to 1/2 inch, plus 100 mesh.

Perlite Expansion Plants

A plant for the expansion of perlite consists of ore-unloading and storage facilities, a furnace-feeding device, expanding furnace, provisions for gas and product cooling, product-classifying and product-collecting equipment, and dust collection equipment. A schematic diagram of a typical plant is shown in Figure 245. A plant producing a number of products has several bins for the storage of different grades of crude perlite. If the minus 100-mesh material is not removed from the perlite ore at the mines, filtered vents are required on the storage bins to prevent dust emissions during ore-unloading operations.

Expansion Furnaces

Vertical furnaces, horizontal stationary furnaces, and horizontal rotary furnaces are used for the exfoliation of perlite, the vertical types being the most numerous. Only a few of the furnaces are refractory lined.

Essentially all perlite furnaces are fired with natural gas. The natural gas rate, amount of excess air, and ore feed rate are adjusted to give a furnace temperature, an effluent gas flow rate, and a material residence time that will yield a product of the desired density. Product densities vary from 2 to 15 pounds per cubic foot, and furnace temperatures vary from 1,450° to 1,800°F. The relationships of temperature and residence time to product density are, for the most part, trade secrets. The expanded product is carried out the top of the furnace by the combustion gases.

Gas and Product Cooling

Cooling by heat exchangers or by dilution with ambient air are the two common methods that have been used. Combinations of the two are also used. The final temperature to which the gases must be cooled depends upon the type of dust collector used, as will be discussed later.

Heat exchangers generally employed are of the tubular type with forced-air convection. Large U-tubes with natural convection would probably be practical but have not been used extensively because of the space requirements. Cooling by dilution greatly increases, of course, the volume of gases to be handled by the dust collector. Some of the smaller plants, however, have used this method satisfactorily.

Product Collectors and Classifiers

Cyclone separators are used to collect the product. If only one product is made, a single cyclone separator is used. To make more than one product, two cyclones in series are usually used, in which case some means is often provided for regulating the collection efficiency of the first cyclone so as to allow a controlled amount of fines to pass through to the second cyclone. The product collected in the first cyclone is used as a plaster and cement aggregate, and the fine product collected in the second cyclone has uses such as filter aid, paint

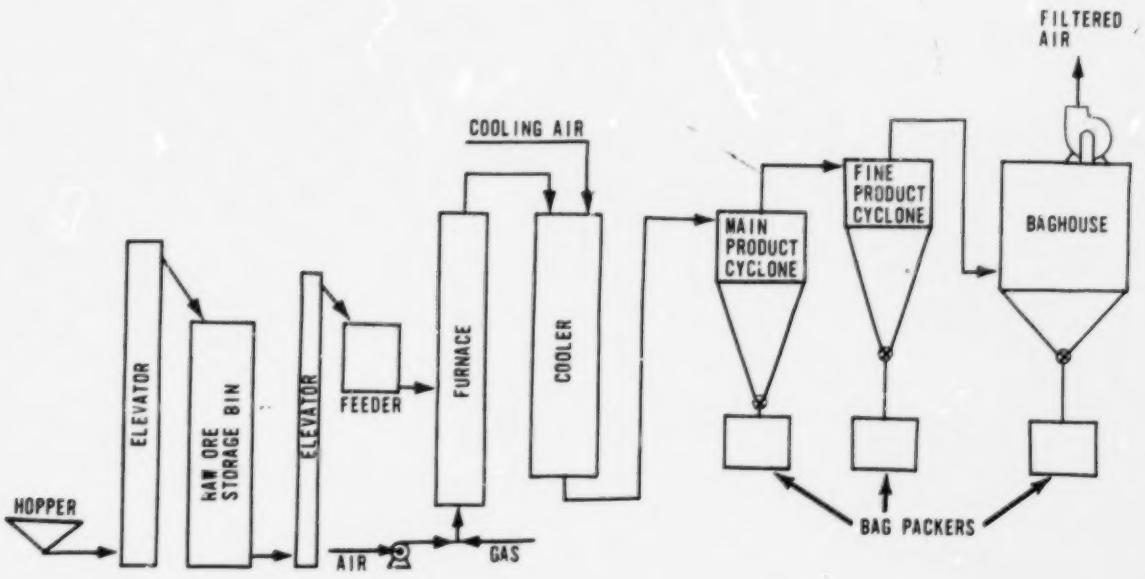


Figure 245. Flow diagram of a typical perlite-expanding plant.

additive, insecticide carrier, and others. The products are packaged in 3- or 4-cubic-foot bags by packing machines with little or no dust loss. If a baghouse dust collector is used, an ultrafine product is collected in the baghouse hopper.

THE AIR POLLUTION PROBLEM

A fine dust is emitted from the outlet of the last product collector. The fineness of the dust varies from one plant to another, depending upon the products desired. In any event, a baghouse is needed to achieve complete control. For example, one plant that was tested produced perlite for use in manufacturing insulated wallboard. Only one product cyclone was used. A particle size analysis of the baghouse catch revealed that 64.3 percent by weight of the sample was minus 200 mesh; approximately 20 percent by weight was less than 5 microns. Specific gravity was 2.69 at 69°F. Table 104 shows a complete particle size analysis of the cyclone and baghouse catches.

HOODING AND VENTILATION REQUIREMENTS

No hooding is required unless ventilation of the sacking machines receiving product from the cyclones is necessary. For most plants, this is not required, and only the air outlet of the last product cyclone needs to be ducted to a dust collector. The volume of ventilation air required depends upon the quantity of air needed to convey the product, the amount of fuel burned, and the volume of dilution air required to cool the effluent sufficiently for admission to a dust collector. The first two factors are fundamental to the basic design of the plant. Once these are known, one can calculate the quantity of dilution air required as a function of the temperature limitation of the dust collector.

AIR POLLUTION CONTROL EQUIPMENT

Simple cyclones have been found inadequate for collecting fine dust from perlite furnaces. Even the relatively high-efficiency devices, such as multiple small cyclones, have been deficient in complying with air pollution prohibitions. Several firms have attempted to use water scrubbers, but most of these installations were unsuccessful. Virtually all the perlite-expanding plants in the Los Angeles area are now equipped with baghouses. These efficient collectors, costing only slightly more than a well-designed scrubber, are able to collect a salable product.

Since the gases from the expanding furnace are at a relatively high temperature, considerable cooling is necessary in order to meet the temperature limitations of any fabric used in a cloth filter dust collector. When Dacron cloth is used, the usual practice is to cool the gases to 400° to 500°F in a tubular heat exchanger. Further cooling takes place in the cyclones, and sufficient dilution air is admitted to cool the gases to 200° to 250°F before they enter the baghouse. Siliconized glass fabric has been used, the cooling accomplished entirely by dilution. Other combinations are of course possible, but these two are most popular.

In order to secure a uniform product from the expansion furnace and classifying system, maintenance of a constant flow rate through the baghouse

Table 104. PARTICLE SIZE ANALYSES FROM THE PRIMARY CYCLONE AND THE BAGHOUSE CATCH OF A PERLITE-EXPANDING FURNACE

Screen mesh size	Particle size analysis, wt %	
	Primary cyclone catch	Baghouse catch
+10	0.4	0.0
-10+30	26.0	0.4
-30+60	30.0	2.7
-60+100	22.2	9.5
-100+200	14.0	23.1
-200	7.4	64.3

Particle size analyses of -200-mesh portion of samples

Diameter (D), μ	Sample with diameter < D, wt %	
	Primary cyclone catch	Baghouse catch
45.7	100.0	--
40.2	99.3	--
36.6	99.0	--
32.9	96.3	--
29.3	93.7	100.0
25.6	90.2	99.4
22.0	85.4	97.6
18.3	80.5	96.4
16.5	77.1	94.5
14.6	71.2	93.6
12.8	63.2	91.5
12.2	60.5	88.5
11.6	57.5	86.1
11.0	55.6	82.1
10.4	52.0	81.2
9.8	48.8	74.2
9.2	46.6	70.6
8.5	42.0	66.4
7.3	35.1	55.2
6.1	27.3	43.0
4.9	19.0	29.4
3.7	11.7	16.7
3.0	7.6	11.5
2.4	6.1	7.0
1.8	3.9	2.4
1.5	3.7	1.5
1.2	3.2	1.2

is highly desirable. In general, the resistance of a baghouse increases as the dust layer builds up. This gives a nonuniform flow rate unless measures are taken to counteract this tendency. Three general methods have been used to maintain relatively uniform flow rates:

1. Use of a single-compartment baghouse with an adjustable restriction in the inlet duct. The restriction is set at a maximum value when the bags are clean and is decreased as the baghouse's resistance increases, and this maintains a relatively constant total resistance. This method requires frequent adjustment of the restriction and reserve fan capacity. When the restriction reaches its minimum value, the process must be shut down.

2. Use of compartmented baghouses, which permits one compartment at a time to be shut off for bag shaking. This produces a resistance that varies cyclicly, but flow variations can be kept within tolerable limits. The greater the number of compartments, the smaller the variations in flow.

3. Use of continuous-cleaning-type baghouses. Included in this category are types using high-pressure blow rings (Hersey types), those using traveling blow chambers on envelope-type bags, and those using pulses of high-pressure air. These types are capable of maintaining almost completely uniform flow rates, but their costs are somewhat greater than those of the other types.

Filtering velocities should be 3 fpm or less for the standard types using woven fabrics and about 10 fpm or less for the Hersey types.

FEED AND GRAIN MILLS

INTRODUCTION

Commercial development of feed mills, based upon scientific animal nutrition, has advanced rapidly since 1930. Enriching feed with vitamins and minerals has accelerated the growth rates of poultry and livestock to nearly double the average growth rates of 1930.

With changes in feeding, the animals are increasingly being moved from cattle range and rural farm forage areas to confined pens and feed lots near urban areas. This transition tends to locate the feed and grain plants in congested areas where many conflicts about air pollution arise. The handling and manufacture of feed and grain products generates many varieties and concentrations of dust. These dusts are the sole air contaminants from these plants.

To pinpoint the sources of dust, a simplified diagram of feed mill flow is presented in Figure 246. The drawing delineates basic equipment in solid lines and dust control equipment in dotted lines. Solid-line arrows indicate the flow of basic material from process to process. Dotted-line arrows indicate the forced discharge of dusty air to collectors.

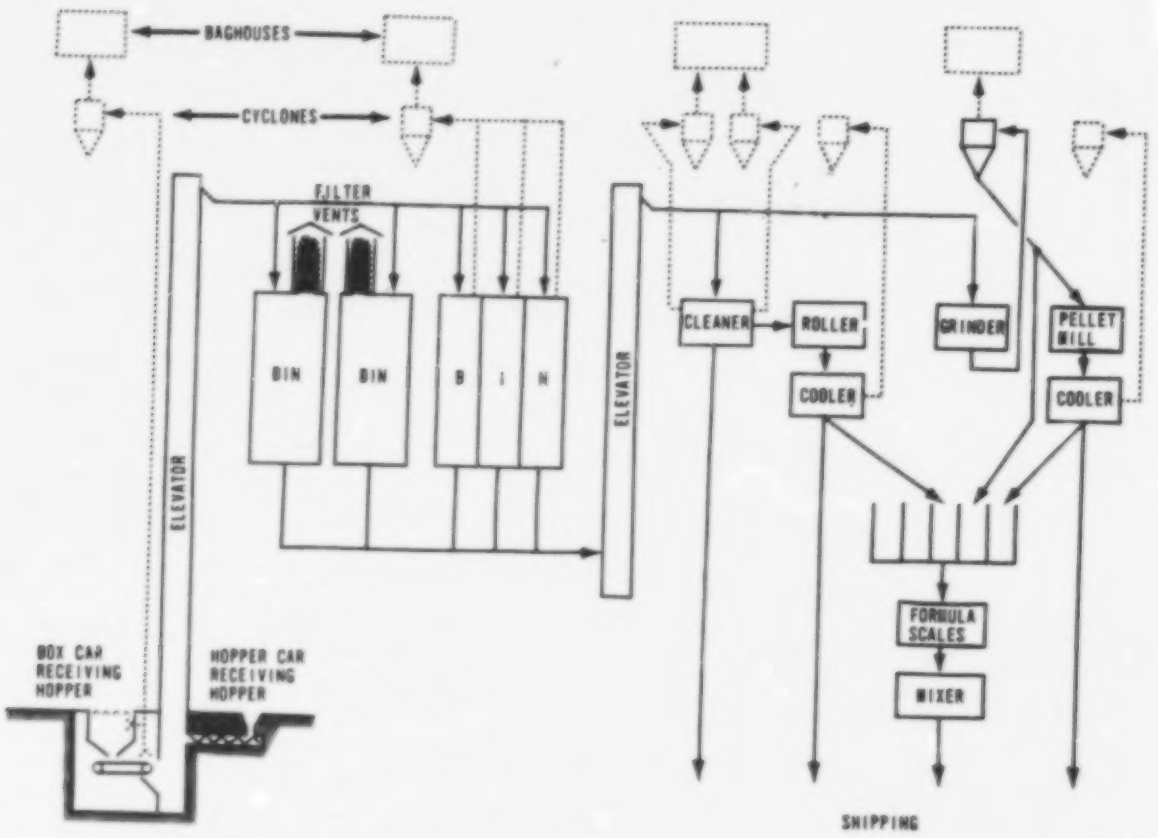


Figure 246. Flow diagram of a simplified feed mill. Basic equipment shown in solid lines, dust control equipment, in dotted lines.

Receiving, Handling, and Storing Operations

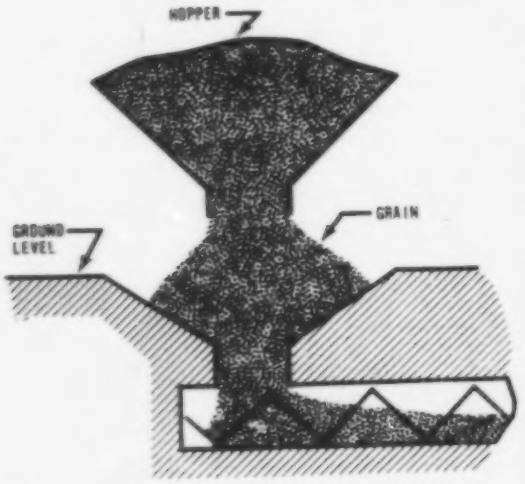
Feed materials are shipped to feed and grain plants in railroad cars and trucks. These carriers may be classified according to the type of unloading operation used.

One class includes hopper bottom railroad cars, trucks and trailers, trucks with self-contained conveyors, and hoist dump vehicles. The flow of materials from these self-unloading shipping containers may be regulated so as to fill an inclined chute or shallow hopper as rapidly as the material is removed. This is the choked-feed method of unloading, in which a solid stream of material moves slowly into the receiving system with little or no dust emissions. Figure 247 illustrates choked-feed receiving from a hopper bottom railroad car. Canvas boots or socks may be fastened to the spouts and extend down within inches of the hopper gratings, though they are not very frequently used.

Another class includes flat bed trucks and box cars capable of being emptied into receiving hoppers only by mechanical plows or shovels. The carrier beds are about 3 feet above the hopper gratings, which are located at track or ground level. The flat bed carriers are usually unloaded into deep, large-capacity receiving hoppers. The excess surge-holding capacity allows enough time between car unloadings for an empty car to be replaced by a full car, while the handling system continues to convey material out of the hopper. This method provides for receiving the maximum number of cars or trucks per day and may also effect some savings in labor costs. Figure 248 shows the unloading of a boxcar into a deep hopper.

Feed materials are less commonly unloaded from carriers by pneumatic conveyors. The material may be fed manually to a flexible suction tube, connected to a pullthrough cyclone, which separates the feed materials from the air conveying system and drops them into a storage bin. Another pneumatic unloading system type uses specially constructed hopper bottom cars or trucks equipped with air or mechanical agitation devices. These devices feed the material through a rotary valve to a pressure-type pneumatic conveyor. The airborne material from this type of conveyor is also separated by a cyclone and dropped into storage.

Grain and feed storage bins may be single or multiple compartmented. They are usually constructed of steel or concrete. Each bin or compartment is enclosed by a dust-tight cover incorporating an ade-



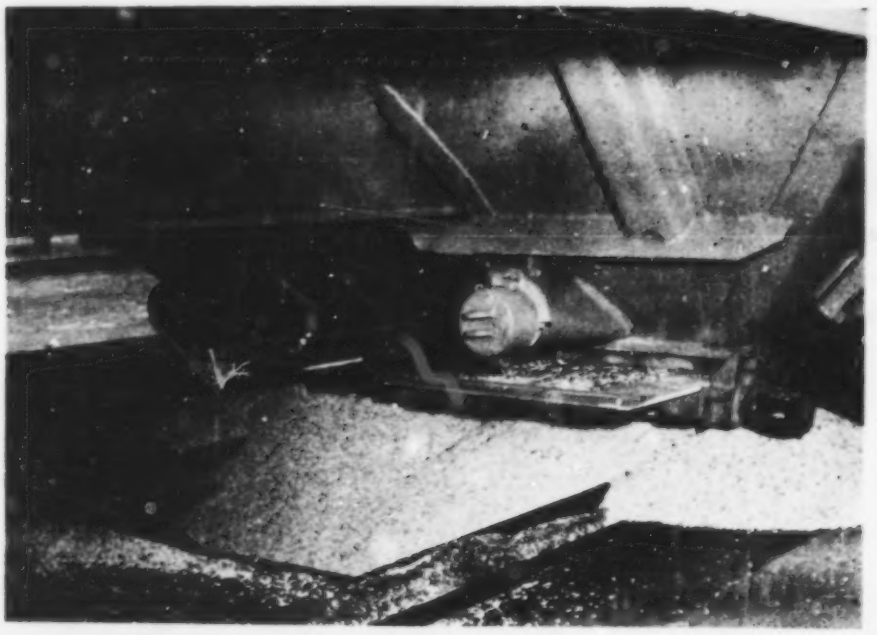


Figure 247. Hopper bottom railroad car unloading grain into a shallow hopper by the choked-feed method (Koppel Bulk Terminal, Long Beach, Calif.).

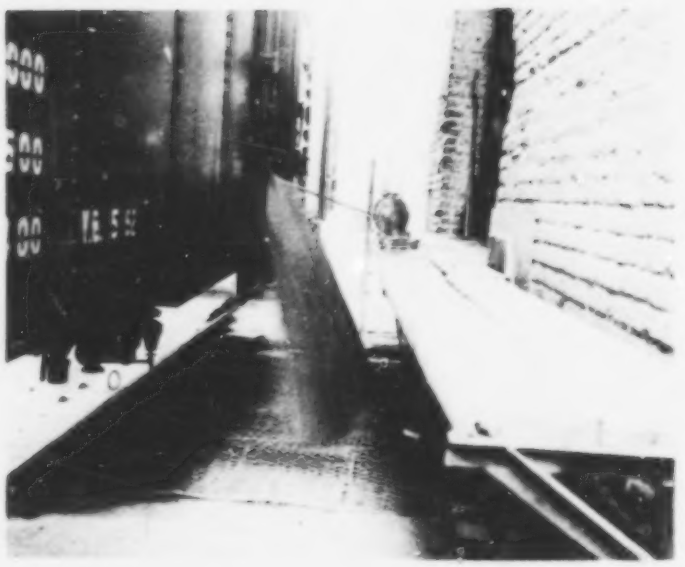


Figure 248. Boxcar unloading grain into deep receiving hopper.

quately sized vent. This vent provides an escape for displaced air during filling and prevents the bin from buckling under external atmospheric pressure during the discharge operation.

Feed-Manufacturing Processes

From the storage bins, whole grains are conveyed to cleaning, rolling, grinding, and other plant processes. The processed grains may be shipped to consumers or held for feed formulation. Finished feed formulas are compounded from vitamins, antibiotics, minerals, and all the processed materials. These compounds may be prepared in the form of finely ground mash, pellets, or mixed mash and pellets. The feeds may be shipped from the mill in plant-owned delivery trucks, common carrier trucks, or by rail.

A certain amount of dockage is acceptable, by government grading standards, in all grains. Dockage is made up of dust, sticks, stones, stalks, stems, weed seeds, and other grains. A portion, if not the majority of this undesirable material, must be removed if the grain is to go into certain processes. The degree of separation required depends upon the actual process, for example, barley to be ground in a hammer mill needs minimum cleaning whereas barley to be rolled requires a high degree of cleaning. In some circumstances, received grains may have been cleaned before elevator storage or as preparation for export shipment, in order to eliminate hazards of spontaneous heating, insect infestation, and so forth.

Cleaning includes the several mechanical processes by which dockage is removed from grain. By the nature of its purposes, cleaning produces a large amount of dust. The amount of dust varies widely with the different field sources of grain and its subsequent handling. A preliminary step in the cleaning process is termed scalping. In this process, the grain is run through a coarse mesh screen in shaker or reel form, to remove sticks, stones, stalks, strings, and similar offal. The grain is

usually poured through the screen at low velocity with little or no aeration; very little dust is generated. The shaker type of scalper may be of dust-tight design with no vent to the atmosphere. Another step is called aspiration. Crosscurrents or countercurrents of air are directed through dispersed falling grain. The process is designed to separate field dust, fibers, chaff, and light trash from the grain. The third step employs a stack of several grading shaker screens to classify the grain. Mixed grains are separated at this point. Noxious weed seeds are also removed, to prevent them from being disseminated.

The three steps of cleaning may be accomplished in separate devices or all in one piece of equipment. A traditional type of cleaner, as shown in Figure 249 combines all three of these steps in one machine. This type commonly employs three integral blowers and has two exhaust airstreams that carry away different types of separated materials.

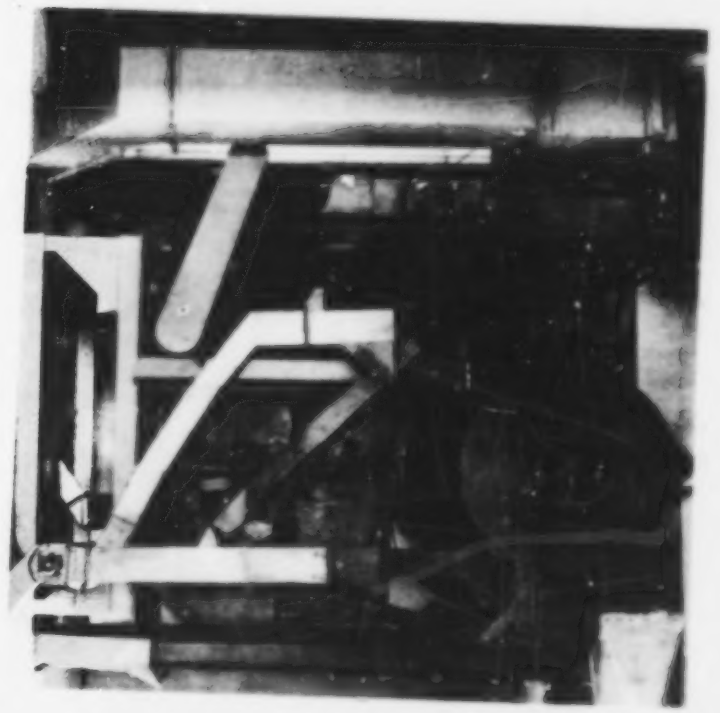


Figure 249. Grain cleaner (Koppel Bulk Terminal, Long Beach, Calif.).

Barley rolling is accomplished in equipment commonly called barley steamers and barley rollers. Oats and milo may be processed in the same equipment. Cleaned grain is conveyed and elevated from storage to an open-coil-type steamer, which heats and moistens the grain. It is then run through steel rollers and dropped into a cooler through which room air is pulled to cool the hot, moist grain.

Many feed grains and some feeds such as copra or cotton seed are ground in hammer mills. This type of mill is so constructed that it is also inherently a centrifugal blower. Granular material is fed into the center of a high-speed rotor, which has pivoted or articulated hammers on the periphery. The material is thrown centrifugally against and through a perforated, peripheral plate or screen. The proper flow of material through the mill requires a strong stream of air. Supplemental air capacity is generally supplied by a pullthrough blower driven integrally from the mill shaft. The ground product is then conveyed pneumatically to a cyclone separator, which delivers the ground meal to storage bins. Size reduction of feed is sometimes accomplished in a burr mill or other type of equipment that requires no airstream for operation.

Pelleted dairy feed consists of several different types of finely ground feed materials, combined with molasses and a binder material, steam conditioned, and compressed into pellets by a pellet mill. From the mill, pellets are dropped into a cooler where a blower pulls room air through them. After their cooling, dairy pellets are usually run across a shaker screen for removal of any small particles that occurred during the breaking of extruded pellets away from the mill die. The particles are usually conveyed pneumatically from the shaker back to the pellet mill feed.

Feed formulations are devised to suit all variations of creature appetites and conditions of livestock production, on a nationwide basis, or for individual flocks and herds. Component grains may be steamrolled, or dusty feed material fines may be pelleted to improve the texture and flavor.

A formulating equipment system consists of from one to three scale hoppers, sized according to the bulk class of products each weighs. Materials may be measured into the scales by simple manual operations or by elaborate pushbutton consoles that operate remote conveyors from multiple storage bins. After the scales there may be a single mixer or a cascade of surge bins and parallel or tandem mixers with oil and molasses sprayers. The batches of finished feed may be conveyed to holding bins, for later transfer to truck or railroad car, or they may be loaded directly to a carrier without holding.

THE AIR POLLUTION PROBLEM

Many feed and grain plants, originally located at crossroads in sparsely settled farm areas, are now surrounded by urban stores, offices, schools, and modern residential developments. As a result of frequent public complaints after community encirclement, the plants must either be relocated in less sensitive industrial areas, or comprehensive dust control programs must be initiated.

There is now active medical research (McLouth and Paulus, 1961) showing the deleterious or toxic effects of feed grain dusts. Many individuals experience bronchial or allergic disturbances after exposure to feed and grain process effluents. Persons affected may be inside a grain-processing plant or even some miles downwind (Cowan et al., 1963).

Pertinent to the control of dust inside plants is the ever-present spectre of fire, sometimes spontaneous. Fire can run along dust deposits on mill beams faster than a man can run to cut it off and can thus envelop an entire building before fire equipment can be used.

The destructive force of cereal dust explosions is well known, especially the secondary type of explosion that occurs after a primary shock wave has lifted and mixed heavy dust deposits with air, creating a massive, explosive mixture.

The vacuum cleaning of mill interiors is, therefore, a constant, expensive chore. A likely answer to the hazards of dust accumulation may be the construction of unhoused feed process systems as is now frequent practice in the power-generating, oil refinery, and chemical process industries.

In undeveloped or farm areas, no practical purpose may be served by preventing feed mill dust emissions, but in urban areas, dust losses from feed materials are likely to cause a nuisance. Basic process equipment for either open or housed plants will be increasingly required to effect dust-tight enclosure by the use of sealants, gasketing, or welded joints. Air vented from equipment will need to be controlled either by filters attached to basic equipment or by duct systems connected to air pollution control equipment.

Feed materials and field run grains, received at the mill, commonly contain much fine dust in addition to long, fiber-shaped dust particles. Fine dust found in grain may include the actual soil in which the grain was grown, owing to wind or rain action in the field. Other fine particles may originate from weeds or insects or be produced from the grain itself, by abrasion in handling and storing. For these reasons, no reliable prediction of the kind and amount of dust in a shipment of field run grain may be expected. The amount of dust found in the many other miscellaneous feed materials varies far more widely than in grains.

The long-fibered dust particles, such as barley beards and even weed seeds and other particles, are much more an expected, characteristic part of any particular grain shipment. These, however, seldom present an air pollution problem.

Table 105 presents the particle size distribution of dusts from a boxcar of barley received in a deep hopper at a feed mill. Dust picked up by a control hood was carried by a blower to a cyclone where the larger particles dropped out and were collected in a sack (sample No. 1). The cyclone then vented to a baghouse, which collected the finer material in a hopper (sample No. 2).

Table 105. PARTICLE SIZE ANALYSES OF THE PRIMARY CYCLONE CATCH AND THE SECONDARY BAGHOUSE CATCH OF DUST FROM A RAILROAD RECEIVING HOPPER HOOD CONTROLLING THE UNLOADING OF A BOXCAR OF FEED-TYPE BARLEY[a]

	Particle size distribution by wt	
Particle size, μ	Sample No. 1 cyclone bottoms, %	Sample No. 2 baghouse hopper, %
0 to 5	0.9	4
5 to 10	0.9	25
10 to 20	3.9	66
20 to 44	9.3	5
44 to 74	12.9	0
74 to 149	16.2	0
149 to 250	5.4	0
Over 250 (60 mesh)	50.5	0

[a]Specific gravity of both samples was 1.8.

Receiving, Handling, and Storing Operations

The dusts that cause air pollution problems in receiving, handling, and storing operations are generally the fine dusts found in field run grains, or in those feed materials from which much dust is generated. When one of these materials is unloaded from flat bed trucks or boxcars to deep hoppers, it is dropped from a height of 3 to 15 feet in sudden surges. The particles in the stream of free-falling material disperse as they accelerate, and inspirate a downward-moving column of air. When the mass hits a hopper bottom, the energy expended causes extreme air turbulence, abrasion, and deagglomeration of the particles. A violent generation of dust occurs. It forms an ascending column that boils out of the opposite end of the hopper. A dust plume of 100 percent opacity and of sufficient volume to envelop a boxcar completely may be formed from the unloading of grain. Figure 250 shows how dust is generated during the dumping of grain from a boxcar into a deep hopper.

Conveying equipment does not usually present difficult dust problems; however, the rubbing friction of screw conveyors, drag conveyors, and bucket elevators on feed and grain abrades these materials, creating fine dust particles. Dust is generated at the transfer points of enclosed conveying equipment, carried through bucket elevators, and emitted at the discharge of the conveyed materials.

Belt conveyors are the most efficient type of handling equipment, especially for large volumes of

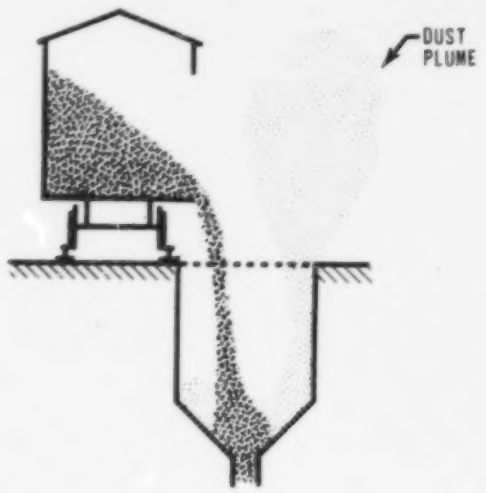


Figure 250. Unloading a boxcar into a deep receiving hopper.

material and for long conveyances. They cause less mechanical abrasion of the material and separate much less of the dusty fines from the grain than screw conveyors do. Dusty air, however, is usually generated at belt transfer points, resulting from aeration of material as it falls onto or away from a belt. A secondary problem with belt conveyors results from materials' adhering to the belt as it turns around the head pulley. These particles, usually coarse, drop from the returning belt along its entire length.

Storage bins vent dust-laden air originating from two sources. One is air displaced by incoming material that falls freely from a spout at the top of the bin, mixing dust with the air in the bin. The other is air inspirated by the flow of incoming material. This air may contain large quantities of dust.

Shipping feed out of the plant, by spout loading into cars or trucks, is similar to the storing operation. Most finished feeds are, however, somewhat agglomerated by molasses or oil additives so that a minimum of dust is generated in the shipping process. Dusty feeds, of course, require special handling when they are bulk loaded into carriers.

Feed-Manufacturing Processes

When grain is unloaded from carriers and conveyed to storage, the granules flow in the form of a thick, bulky stream that encloses and retains most of the dust content. Thus the major proportion of dust contained in the original grain shipment remains to be removed by cleaning equipment that employs large quantities of air. The dust must be separated before this air is discharged to the atmosphere.

When a large grain shipment is received, most carloads may contain a uniformly low content of fine dust. The last several carloads, representing a cleanup of fines that became segregated in handling and storage, may be excessively dusty.

Grain rolling and pelleting produce moist, agglomerated particles with no dust emissions from the coolers.

In size reduction of whole grains or other feed materials, the amount of dust discharged from the pneumatic conveyor cyclone may increase as the materials are more finely ground. The character of the material, however, is the chief determinant of the dust generated.

During the formulating and mixing, some open-top dump or cut-in hoppers, used to combine dust-generating ingredients for mixing, require control. The methods of material handling such as free fall, choke feed, and so forth determine the character of the emissions in these open systems. Mixing systems now tend to be designed for dust-tight enclosures of all conveying equipment, with filter vents on surge bins and mixers. This plan of dust control requires no other control equipment.

Poultry pellets are usually compounded with fish oil or animal fats instead of molasses. If no fat or pellet binder material is used, poultry pellets that have been run through a shaker for removal of fines may be moderately dusty. A totally dust-enclosed type of shaker is recommended to prevent dust loss to the air.

Care must be taken in returning collected dust to a basic equipment system, or a heavy, recirculating dust load may be created.

HOODING AND VENTILATION REQUIREMENTS

Hooding requirements in a feed mill are limited to those for deep receiving hoppers, open conveying equipment, and formulating hoppers in which the material free falls without being enclosed. No hooding is required for choke-feed hoppers, enclosed conveying equipment, bins, or for any of the manufacturing processes.

Receiving, Handling, and Storing Operations

A preferred method of hooding a deep receiving hopper, to control dust emissions, is to exhaust air from below the grating. As shown in Figure 251, a hopper with V-shaped baffles below the grating is vented to control equipment. The baffles reduce the area open to the atmosphere and also reduce the air capacity required to vent the hopper face. If the hopper is in a building, or completely sheltered from winds, an indraft velocity of 100

fpm through the open area of the hopper, between baffles, may be effective. If moderate winds of 3 or 4 mph are to be encountered, an indraft velocity of 300 fpm may be required. For higher winds, fence-like baffles around the top of the hopper may be required, to prevent the winnowing action of strong wind currents across the hopper grating.

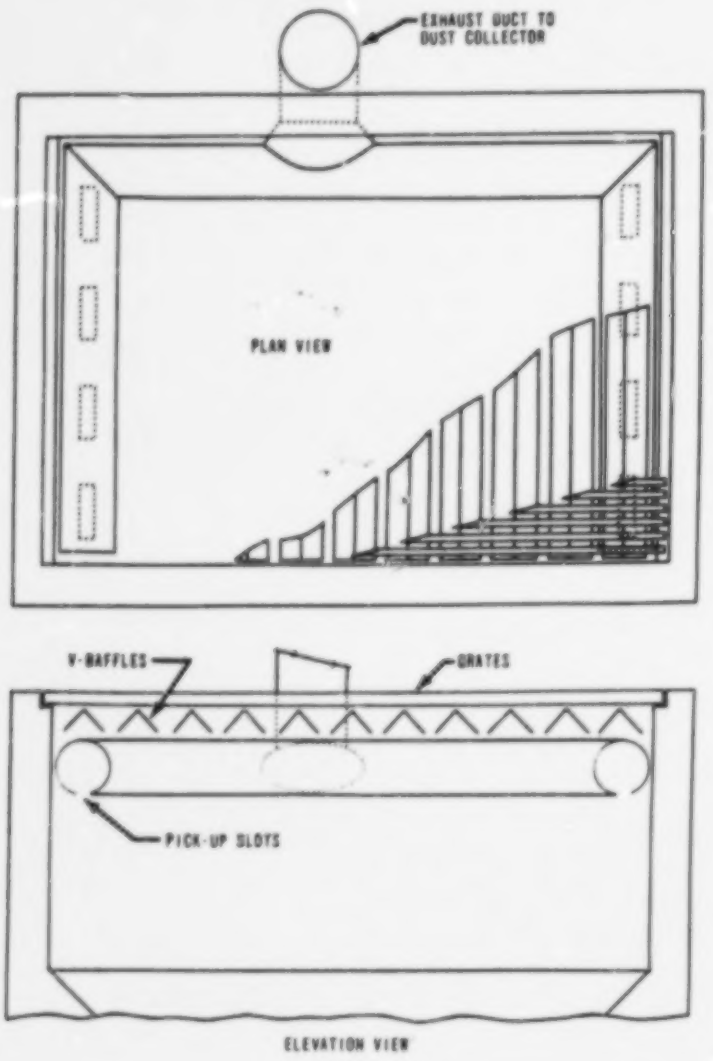


Figure 251. Dust control hooding of deep receiving hopper.

Belt conveyors are almost never fully enclosed. They must, therefore, be hooded at both the point where material is loaded onto the belt and the point where it is discharged from the belt. The loading and transfer chutes must be cleverly designed to reduce dust generation at these locations. The first objective is to design chutes so as to direct the flowing material in the direction of belt travel. The second objective is reduction of the open area exposed to the atmosphere. The enclosing of the transfer point may be sealed right down to the belt, with flexible rubber flaps. Moderate volumes of pick-up air then suffice to control the dust. Indraft velocities into the open-face areas of hoods, which control belt transfer, should follow the same criterion of 100 to 300 fpm recommended for receiving hoppers.

The secondary problem posed by material that does not fall cleanly away from the belt into the discharge chute may be remedied by the use of a rotary brush. The brush is installed inside the combined discharge chute and control hood, with a flexible rubber wiper to close the hood up to the return belt. The brush is usually driven by chain or V-belt from the head pulley shaft at a speed 2 or 3 times that of the pulley. This brush should be made of long-fibered nylon bristles since it is subject to damage by any sharp metal fasteners in the conveyor belt splice.

In a fully enclosed materials-handling system with one or more conveyors and elevators in series, dust-laden air may be conducted through the entire system and emitted at the location of the final material discharge. Connecting a duct to the last piece of equipment in order to vent the entire system to control equipment is, therefore, desirable.

In venting storage bins and containers, no hooding is required; the filter vent or control system duct attaches or connects directly to the bin vent. The volume of air exhausted is simply the volume rate of the bulk material stream flowing into the bin and displacing air.

Feed-Manufacturing Processes

The feed-processing machines do not commonly require accessory hoods for picking up their effluents. The hooding is an integral part of most basic machines. Cleaners and hammer mills, additionally, have integral blowers that may be vented to the control equipment.

Pellet and rolled-grain coolers are designed with integral hooding. The air capacity is based upon the requirements for cooling and drying of the heated feed material only.

Floor level cut-in hoppers or scale hoppers may be hooded and vented to control equipment. On the assumption they are inside a building, 100-fpm face velocity into the hood should be adequate.

AIR POLLUTION CONTROL EQUIPMENT

Air pollution from feed and grain mills consists entirely of dusts. These dusts, though varied, may be collected by inertial devices and fabric filters. In practice, all the collected material may be returned to the process. Cyclones may be adequate as dust control equipment for feed plants in farm or nonsensitive areas. Elsewhere, in urban or

sensitive communities where nuisance complaints and air pollution regulations take effect, baghouses are needed for final dust control of feed plants.

Table 106 shows the results of three tests for determining the loss of grain dusts from cyclone outlets to the atmosphere.

Receiving, Handling, and Storing Operations

The deep free-fall type of receiving hopper is not normally controlled in farm or nonsensitive areas. In urban areas it may be adequately controlled only by a baghouse or cyclone-baghouse combination.

Dust emanating from pneumatic unloaders, pneumatic conveyors, belt conveyors, and elevators need not be collected in nonsensitive areas. Otherwise, baghouse control is needed in urban areas.

Storage bins and shipping containers need no control in nonsensitive areas. Elsewhere the two applicable control methods are (1) to exhaust the bins and containers by duct connection to baghouse control systems, or (2) to employ some form of a filter vent attached directly to each bin or shipping container.

Feed-Manufacturing Processes

In urban or sensitive areas, grain cleaner and hammer mill cyclones and cut-in hopper hoods need to be controlled by baghouses. In undeveloped areas, cleaner and hammer mill cyclones may be vented to the atmosphere. If, however, much grain is to be ground in a hammer mill, the use of a baghouse to prevent economic loss may be feasible.

The hot, moist, agglomerated particles in rolled-grain cooler exhausts or in pellet cooler exhausts are adequately controlled by a cyclone in any type of area, though condensed water vapor plumes from the cyclone are very noticeable under high-moisture and cold-weather conditions.

Filter Vents

A filter vent consists of a filter cloth bag or sock, usually made of cotton sateen, tightly fastened over a vent. A sheet metal enclosure is added if the vent is exposed to weather. The same control principle can also be used in loading feed into trucks or railroad cars, through downspouts inserted into the hatches. A filter vent skirt is sealed around both the spout pipe and the hatch opening, as shown in Figure 252.

The pneumatic loading of boxcars may be controlled by a flat filter cloth screen of cotton duck or cotton drill across the door. In loading a ship's hold, at a high-volume rate with dusty material, effective control may be obtained with similar filter cloth screens. A hatch opening, up to 25 by 30 feet in size, can be enclosed by two 25- by 40-foot screens, with a wide center overlap around the downspout, as shown in Figure 253.

Filter vents vary in size, from about 1 foot in diameter by 2 feet in height, to perhaps 3 feet in diameter by 5 feet in height. They may, however, be of any size or shape. Filtering velocities should not exceed 4 to 6 fpm for control of miscellaneous feed material dusts. Higher velocities may be used in filtering coarse dust or when a filter is used for short or intermittent periods of operation. Some provision for shaking the bags should be made when necessary. Insect infestation should also be considered when filter bags are not cleaned or changed from one bin filling to the next.

Cyclones

Cyclones are used with great versatility in feed mills. They are an integral part of almost every equipment system that handles air. In practice, nearly all cyclones found in feed plants are of the simple, low- or medium-efficiency types. High-efficiency, multiple cyclones are subject to excessive operational costs and maintenance problems.

Table 106. DUST LOSSES FROM CYCLONES

Grain	Malted barley		Feed barley	Milo	
Basic equipment	Grain cleaner		Hammer mill	Grain cleaner	
	Test No. 1	Test No. 2			
Process wt, lb/hr	53,000	50,000	10,350	11,250	
Exhaust air volume, scfm	2,970	2,970	3,790	First cyclone	Second cyclone
				3,680	2,610
Dust concentration, gr/scf	0.194	0.160	0.488	0.058	0.006
Dust loss, lb/hr	4.95	4.07	15.8	1.83	0.13

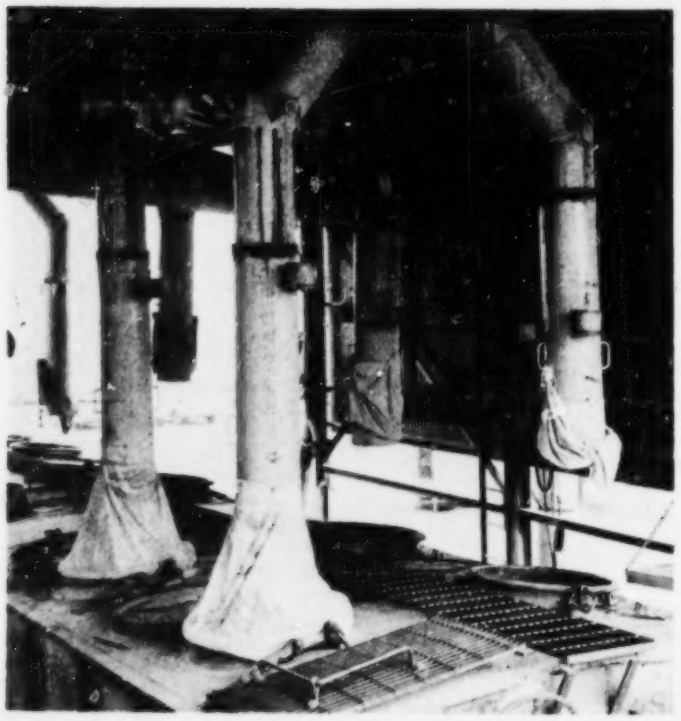


Figure 252. Counterweighted, telescoping downspouts used to fill a hopper car. Loading is controlled by filter vent skirts (Ralston Purina Company, Los Angeles, Calif.).

Cyclones collect almost all grain dusts larger than 10 to 20 microns in diameter. They collect only a very small proportion of the particles smaller than 10 microns, as shown in Table 105. Thus, their percentage efficiency, that is, the proportion of the total material weight caught to the total material weight in the exhaust air stream, is very high. Nevertheless, the proportion of fine dust particles caught by a cyclone to the total number of fine dust particles in an exhaust stream is invariably very low. These fines are the particles that become airborne and constitute an air pollution problem. Special design information for cyclones is given in Chapter 4.

Baghouses

Baghouses for most mill operations tend to be of the simplest and least expensive types, and use cotton sateen in most cases. Hand shaking of the filter bags is preferred, to avoid any risk of fire from automatic shaking equipment. Filtering velocities are from 2 to 3 fpm for continuous operation, and up to 6 fpm for intermittent use. Cost of the baghouse may be as low as $1.00 per square foot of filter cloth.

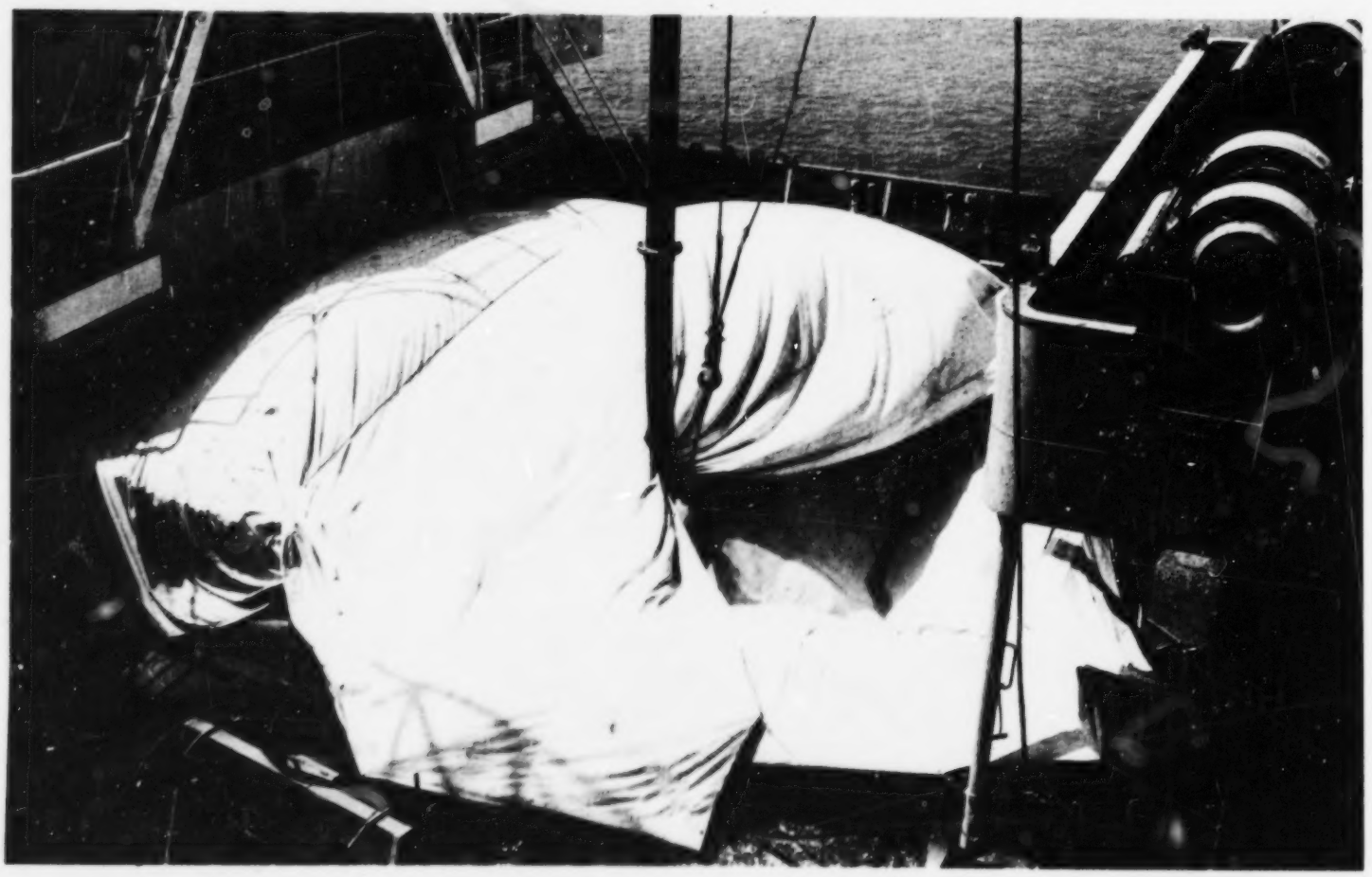


Figure 253. Loading alfalfa pellets into a ship's hold, controlled by two 25- by 40-ft filter cloth screens (Pacific Vegetable Oil Corporation, Long Beach, Calif.).

The static pressure drop through the baghouse is, in most cases directly proportional to the filtering velocity. Where a dust cake is allowed to build up for several hours before the shaking or a permanent low-porosity cake has developed, the pressure drop in inches of water column may be estimated as equal to the filtering velocity in fpm. Airstreams with heavy dust or material loadings are usually exhausted to a primary separator cyclone and then to a baghouse. This method relieves the baghouse of handling an excessive volume of bulk material.

Larger feed mills and those operated in conjunction with flour and cereal plants are usually equipped with the more sophisticated and expensive types of baghouses. These use elaborate, mechanically programmed bag shaking with filtering velocities as high as 10 fpm. Reverse-jet and reverse-air-blowing types are also used. One modern feed and grain terminal, shown in Figure 254, makes very extensive use of reverse-jet baghouses. It is probably the world's most completely controlled feed and grain terminal facility. Baghouses, as shown in Figures 255 and 256, control dust from truck- and railroad-receiving hoppers. Several other baghouses, which may be seen in Figure 254, control all the material-handling conveyors and elevators, storage and weighing facilities, and grain-cleaning equipment. Another baghouse provides ventilation to the hold of the ship, which is covered by filter cloth screens during the loading operation. The control equipment incorporated in this facility prevents any visible emissions and is an outstanding example of the control of air pollution by this industry.

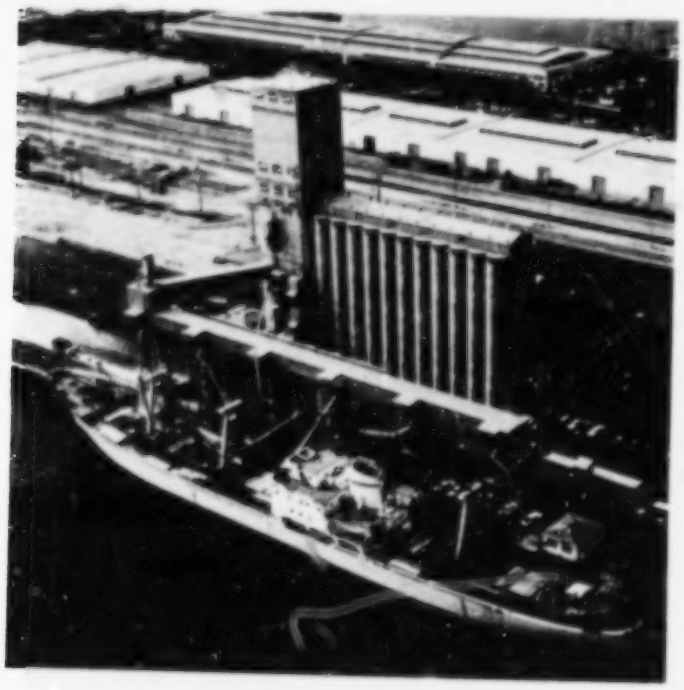


Figure 254. Modern bulk feed and grain terminal with reverse-jet baghouses controlling all operations (Koppel Bulk Terminal, Long Beach, Calif.).

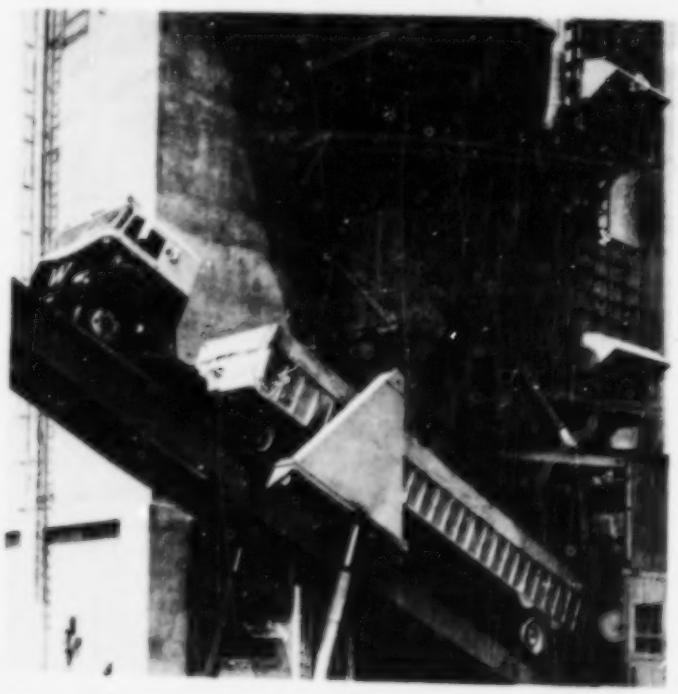


Figure 255. Truck-receiving station with baghouse control of the receiving hopper (Koppel Bulk Terminal, Long Beach, Calif.; and Wunsch Harvesters, Phoenix, Ariz.).

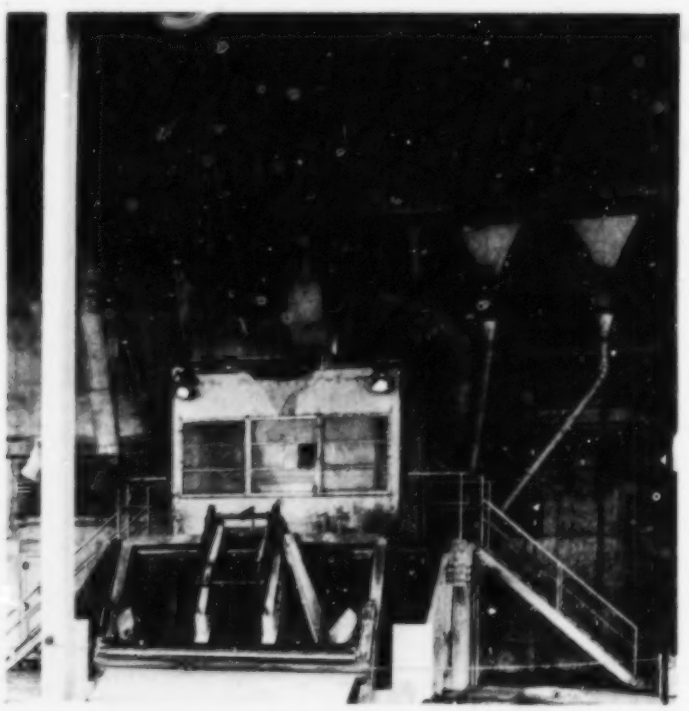


Figure 256. Automatic boxcar-unloading system with baghouse control of the receiving hopper (Koppel Bulk Terminal, Long Beach, Calif.).

PNEUMATIC CONVEYING EQUIPMENT

INTRODUCTION

Pneumatic conveying involves the movement of powdered, granular, or other free-flowing material in a stream of air. The bulk of the material is separated from the conveying air in a product collector, usually a cyclone separator. If the air discharge contains an appreciable amount of dust, it must be passed through a dust collector before being discharged to the atmosphere. A cloth filter dust collector is almost invariably used for this purpose. The weight of dust passing the product collector is normally very small in proportion to the weight of material conveyed, but it is usually of very fine particle size, a relatively small amount of which may result in excessive opacity.

Types of Pneumatic Conveying Systems

In general, there are two types of pneumatic conveying systems: Negative-pressure systems, characterized by low capacity and low pressure

losses; and positive-pressure systems, characterized by high capacity and high pressure losses (Fischer, 1958). To convey from several points to one point, a negative-pressure system is usually used. To convey from one point to several points, a positive-pressure system is usually used.

In a negative system, the material is drawn into the conveying line by suction created at the far end of the system by a centrifugal fan or a rotary positive-displacement blower. The product is collected in a cyclone separator, which has a rotary airlock at its base enabling it to discharge material continuously while maintaining the vacuum. The fan or blower is located on the air discharge side of the cyclone to prevent excessive wear from product abrasion. Narrow-blade centrifugal fans and cyclones are often made as integral units, as shown in Figure 257. The filter is on the discharge side of the fan. A rotary positive-displacement blower can also be used in a negative system. The much higher vacuum produced by this unit gives it a much greater conveying capacity, but requires that the cyclone collector be of heavier construction. The close clearances within these machines usually require that a filter be placed on the inlet side of the pump to prevent dust from being drawn through the pump.

In positive-pressure systems, the air-moving unit is at the head of the line instead of the end. Material is fed into the airstream by a rotary airlock or feeder and is blown to its destination. Rotary positive-displacement blowers or sliding-vane rotary compressors are used in positive-pressure systems. High pressures obtainable with these units permit relatively large quantities of materials to be conveyed with smaller volumes of air than can be handled in a negative system. This permits the use of smaller diameter conveying lines and smaller dust filters since the filter unit is generally rated on the amount of air it can handle. The filter is placed at the end of the system to filter the air discharging from the product collector, as shown in Figure 258.

Types of Air-Moving Used in Conveying

The different devices used for moving air in conveying systems are characterized principally by the pressure that can be developed. The following four groups (see Figure 259) include most of the devices used:

1. Industrial exhausters. These centrifugal fans have a pressure limit of about 16 inches water column. The weight of material conveyed is only a fraction of the weight of air moved. Their use for conveying is usually limited to bulky,

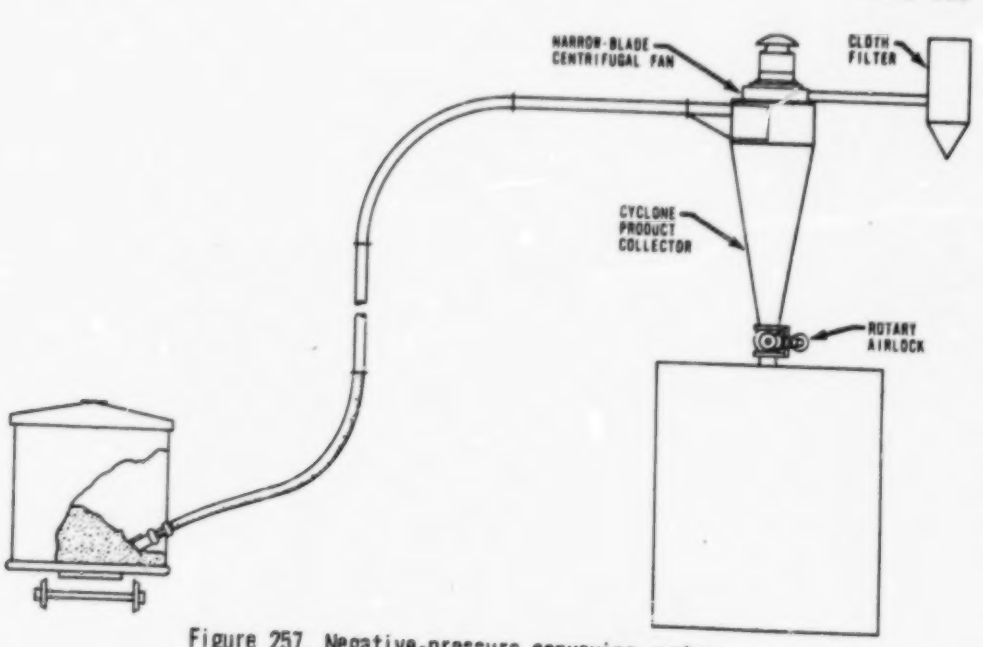


Figure 257. Negative-pressure conveying system.

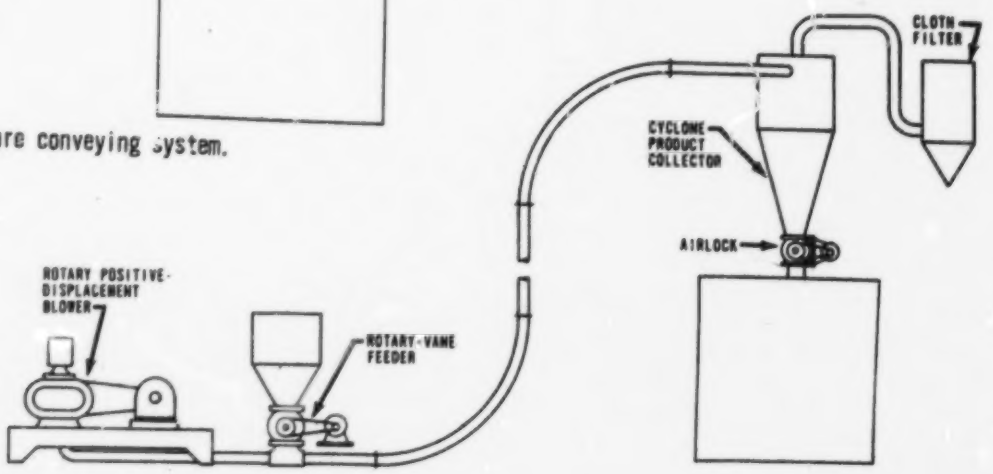
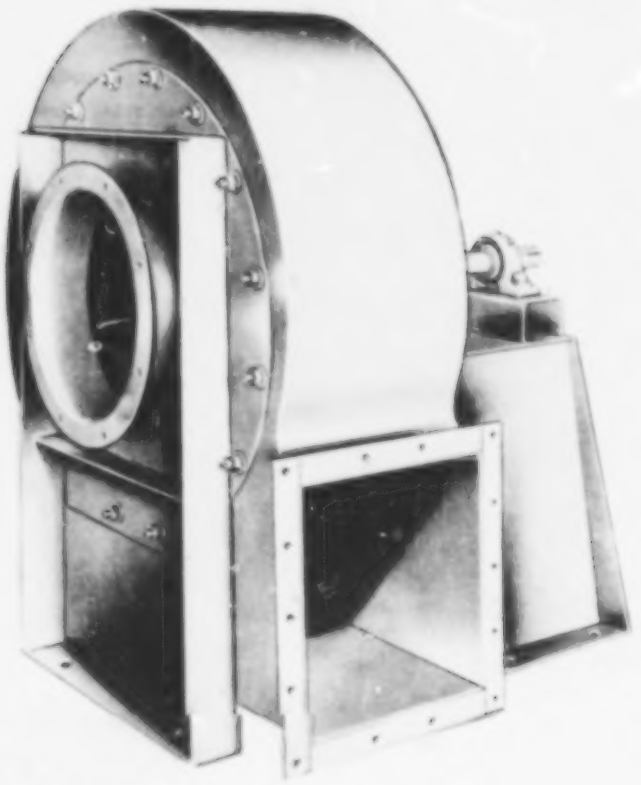
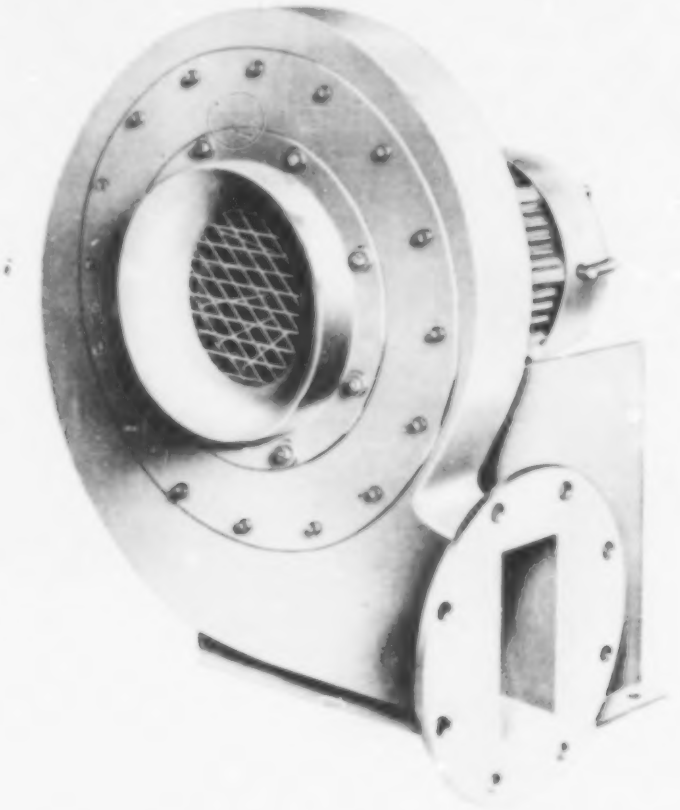
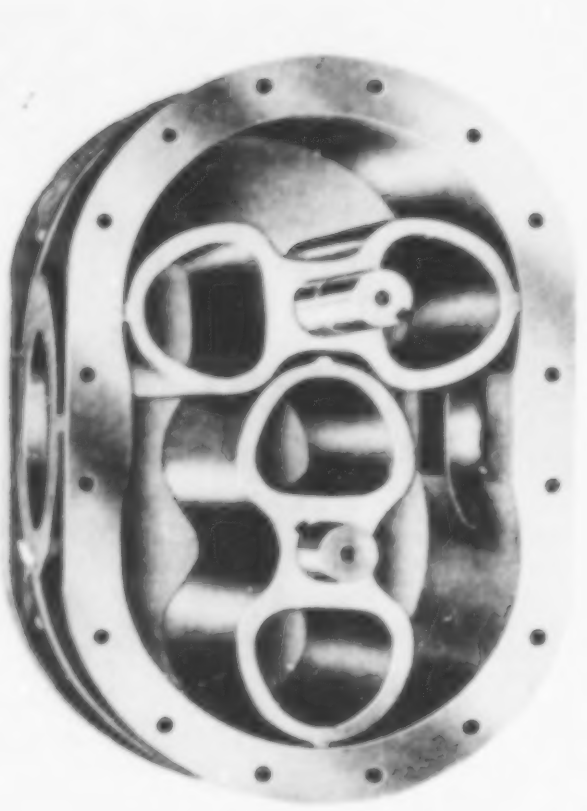


Figure 258. Positive-pressure conveying system.







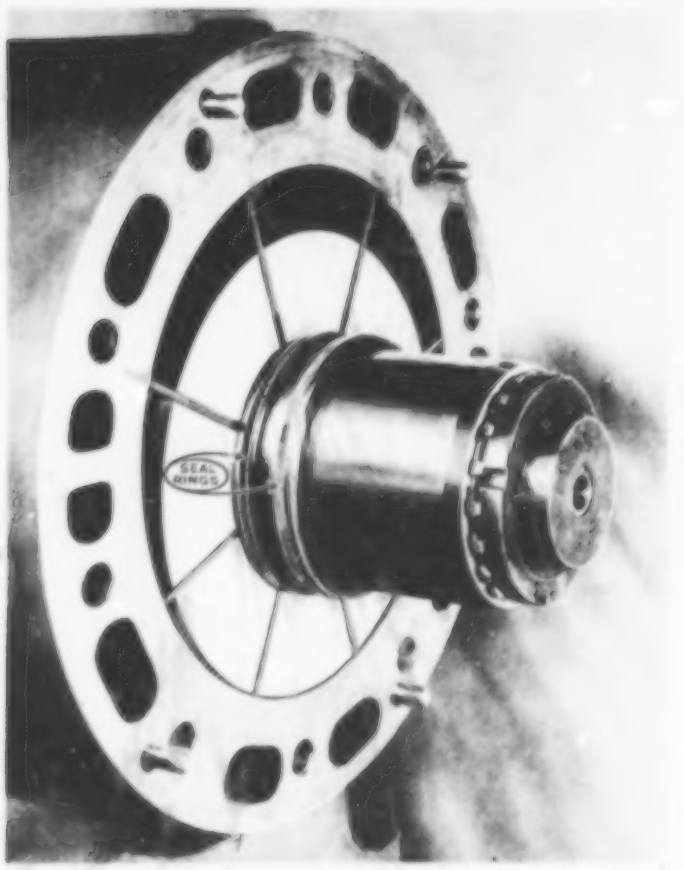


Figure 259. Types of air-moving devices used in pneumatic conveying systems: (top left) industrial exhauster (Chicago Blower Corp., Franklin Park, Ill.); (top right) narrow-blade centrifugal fan (Chicago Blower Corp.); (bottom left) rotary positive-displacement blower, (Sutorbilt Corp., Los Angeles, Calif.); (bottom right) sliding-vane rotary compressor, (Fuller Company, Catasauqua, Pa.).

low-density materials such as sawdust, wood shavings, cotton, and other fibrous materials. They are used extensively to convey materials from cutting, shredding, and grinding machines to storage or further processing.

2. Narrow-blade centrifugal fans. These fans can develop pressures of up to 50 or 60 inches water column. Weights of material conveyed are of the same magnitude as the weight of conveying air. These fans are frequently mounted as an integral part of a cyclone collector. They are extensively used to unload grains and other free-flowing materials. Their use is confined almost exclusively to negative-pressure systems. Conveying distance is limited to about 150 or 200 feet at any practical conveying rate. Two of these fans are sometimes placed in series to give additional capacity or extend the conveying distance.

3. Rotary positive-displacement blowers. These units can produce pressures up to 15 psi. The weight of material conveyed is several times the weight of the conveying air. They can convey for distances of several hundred feet. They are used in both positive- and negative-pressure systems.

4. Sliding-vane rotary compressors. These machines operate in the pressure range of 15 to 50 psi for single stages and up to 100 psi for double stages. They are water jacketed to dissipate the heat of compression and can convey for distances of several thousand feet at very high ratios of solids to air.

Preliminary Design Calculations

The basic problem in design is to determine the energy requirements. These can be expressed in pressure and volume units, and from these units, the size of the blower and the required horsepower can be estimated. These procedures are useful, for preliminary estimating purposes, to those contemplating the installation of a pneumatic conveying system, and would also be useful to an air pollution control official in evaluating a proposed conveying system for permit requirements.

The first step in designing a conveying system is to determine the required conveying velocity. Many theoretical methods of making this determination have been proposed. These methods, however, give only the balancing or floating velocity, such as the terminal velocity given by Stokes law. In order to ensure sustained movement of solids, a velocity considerably in excess of the floating velocity must be used. Hence, reliance upon empirically determined velocities is usually necessary. Table 107 gives velocity ranges found satisfactory for a number of materials.

Fischer (1957) divides the energy requirements into two categories, one for overcoming material losses and the other for overcoming air losses. Air losses are those caused only by flow of the air. Material losses are the additional losses due to conveying the material. He subdivides the material losses into four groups and estimates them by the following empirical relationships:

1. Acceleration. Energy required to bring the material from rest up to conveying velocity is given by the formula

$$E = MV^2/2g \qquad (104)$$

where

E = energy, ft-lb/min

M = solids moved, lb/min

V = velocity, ft/sec

g = acceleration due to gravity, ft/sec^2.

2. Lifting energy. Energy required to lift a given amount of material a given distance can be expressed as

$$E = M(d_v) \qquad (105)$$

where d_v = vertical distance, ft.

3. Horizontal requirements. The energy required to move a material in a horizontal duct can be estimated by the empirical formula

$$E = M(d_h)(f) \qquad (106)$$

where

f = coefficient of friction (calculated as the tangent of the angle of slide) between the material being conveyed and the material from which the duct is made

d_h = horizontal distance, ft.

4. Bends and elbows. The weight of solids moving around the bend is multiplied by the centrifugal force imparted to it according to the formula

$$E = (MV^2/gR)(d)(f) \qquad (107)$$

where

R = radius of bend, ft

d = distance around bend, ft.

Table 107. VELOCITIES FOR LOW-PRESSURE PNEUMATIC CONVEYING SYSTEMS
(Alden, 1948)

Material	Velocity, fpm
Ashes, clinkers, ground	6,000 to 8,500
Barley	5,000 to 6,500
Cement, Portland	6,000 to 9,000
Coal, powdered	4,500 to 6,000
Coffee beans, stoned	3,000 to 3,500
Coffee beans, unstoned	3,500 to 4,000
Cork, ground	3,500 to 5,500
Corn	5,000 to 7,000
Cotton	4,000 to 6,000
Cotton seed	4,000 to 6,000
Flour	3,500 to 6,000
Hemp	4,500 to 6,000
Hog waste	4,500 to 6,500
Jute	4,500 to 6,000
Lime	5,000 to 7,000
Metal turnings	5,000 to 7,000
Oats	4,500 to 6,000
Pulp chips	4,500 to 7,000
Rags	4,500 to 6,500
Rye	5,000 to 7,000
Salt	5,500 to 7,500
Sand	6,000 to 9,000
Sawdust	4,000 to 6,000
Sugar	5,000 to 6,000
Tanbark, dry	4,500 to 7,000
Tanbark, leached, damp	5,500 to 7,500
Wheat	5,000 to 7,000
Wood flour	4,000 to 6,000
Wool	4,500 to 6,000

Air losses are calculated by the methods given in Chapter 3. Cyclone collector losses range from 2 to 4 inches of water column, and cloth filter resistances range from 3 to 5 inches of water column.

To illustrate the calculation methods, a sample problem will be worked.

Example 31

Given:

Material, salt
Conveying rate, 15,000 lb/hr
Horizontal distance, 300 ft
Vertical distance, 70 ft
Three 90° elbows of 40-ft radius
Angle of slide, 35° (tangent of 35° = 0.7).

Problem:

Calculate the required power input.

Solution:

1. Mass rate:

With reference to Table 107, a conveying velocity of 6,500 fpm is selected (108.3 ft/sec).

Mass rate = 15,000/60 = 250 lb/min

2. Material losses:

Acceleration loss = $MV^2/2g$ =

$$\frac{250(108.3)^2}{2(32.1)} = 54,500 \text{ ft-lb/min}$$

Lifting energy = $M(d_v)$ = 250 x 70

= 17,500 ft-lb/min

Horizontal loss = $M(d_h)(f)$

250(300)(0.7) = 52,500 ft-lb/min

Elbow losses = $3(MV^2/g\ R)(d)(f)$

$$= \frac{3(250)(108.3)^2}{32.1(4)} \times \frac{2(3.14)(4)(0.7)}{4}$$

= 301,000 ft-lb/min

Total material loss = 54,500 + 17,500

+ 52,500 + 301,000 = 425,500 ft-lb/min

Assume a 5-inch line:

$$\text{Volume} = \frac{3.14}{4} \times \frac{5^2}{12} \times 6,500 = 885 \text{ cfm}$$

Convert material loss to pressure drop:

$$\frac{425,000 \text{ ft-lb/min}}{885 \text{ ft}^3/\text{min}} = 481 \text{ lb/ft}^2$$

Convert pressure drop to inches of water column:

$$\frac{(481 \text{ lb/ft}^2)(12 \text{ in.})}{62.4 \text{ lb/ft}^2} = 92 \text{ in. WC.}$$

3. Air losses:

Total equivalent length of duct

$$= 300 + 70 + \frac{3(2)(3.14)(4)}{4} = 389 \text{ ft}$$

The friction loss cannot be read directly from the Air Friction Chart (p. 46) because it is off the

chart. Read the loss at 5,000 fpm and multiply by $(6,500/5,000)^2$.

$$\text{Friction loss} = 8.9\,(6,500/5,000)^2$$

$$= 15 \text{ in. WC per 100 ft of duct}$$

$$\text{Total duct loss} = (15)\frac{389}{100} = 58 \text{ in. WC}$$

Assume a cyclone loss of 3 in. and a filter loss of 4 in. Total air loss = 58 + 3 + 4 = 65 in. WC

4. Total pressure loss:

Loss = 92 + 65 = 157 in. WC, or

$$(157 \text{ in.})\ \frac{(62.4 \text{ lb/ft}^2)}{12 \text{ in.}}\ \frac{(1 \text{ ft}^2)}{144 \text{ in.}^2}$$

$$= 5.7 \text{ lb/in}^2.$$

5. Required power input:

A rotary positive-displacement blower will be used in a positive-pressure system such as shown in Figure 259.

Assume a blower efficiency of 60%. The required power input is:

$$\frac{(5.7)(144)(885)}{33,000(0.6)} = 37 \text{ hp}$$

THE AIR POLLUTION PROBLEM

The tendency of dust to be emitted from the product collector is determined largely by the amount of fine material in the product. For finely pulverized materials such as cement and flour, a dust filter is absolutely necessary both from the point of view of loss of product and creation of a dust nuisance. For some materials, the amount of foreign material determines the need for a dust filter. For instance, whole grains do not require a filter if they are completely clean; however, they usually contain enough dirt to require a filter.

AIR POLLUTION CONTROL EQUIPMENT

A conventional baghouse is the usual dust filter used, though reverse-air cleaning types are also used. The dust filter for high solids-to-air systems may consist of cloth filter tubes mounted on top of a storage bin, which is the product collector. Cloth tubular filters are sometimes mounted integrally with cyclone product collectors. The filter tubes are mounted in a cylindrical housing whose lower part is a cyclone separator. The filter housing is divided into four compartments with automatic shaking devices to allow continuous operation.

Filtering velocities commonly used range between 2 and 4 fpm. The optimum velocity varies with particle size and the tendency of the dust to pack. In general, the lower velocities tend to give more trouble-free operation and it is seldom profitable to economize by increasing the filtering velocity.

DRIERS

INTRODUCTION

A drier may be defined as a device for removing water or other volatile material from a solid substance. Air contaminants emitted are dusts, vapors, and odors. Several driers for specific products and processes have been discussed in other sections. In this section, some general characteristics of driers and some details of a few specific types will be considered.

Rotary Driers

A rotary drier consists of a rotating cylinder inclined to the horizontal with material fed to one end and discharged at the opposite end. In the most common type, heated air or combustion gases flow through the cylinder in direct contact with the material. Flow may be either parallel or countercurrent. This type is called a direct rotary drier. In another type, called an indirect rotary drier, heat is applied by combustion gases on the outside of the cylinder or through steam tubes inside the cylinder. In this type, a flow of air is maintained through the drier to assist in the removal of water or other vapors. In some cases, for example, in heating of organic compounds for thermal decomposition only, the process may be accomplished without air movement through the drier.

The direct rotary drier has flights, which lift the material and shower it down through the gas stream as shown in Figure 260. Thus, it has a very high potential for dust emissions. It cannot be used for drying fine materials because loss of product would be excessive. Indirect rotary driers have a much lesser tendency to emit dust. They are the usual choice when a continuous drier for powdery material is required.

In 1960, the Barber-Greene Company completed a comprehensive testing program on full-scale rotary driers to evaluate the effects of the various design parameters. Over 600 individual test runs were completed, and the company spent over $175,000 of research funds for the project.

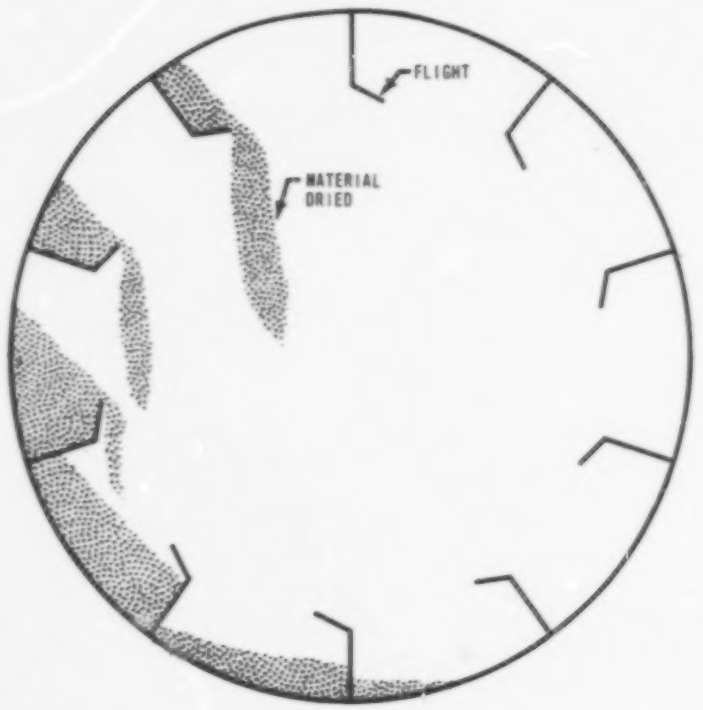


Figure 260. Typical flights used in rotary driers.

The most important of the factors influencing drier selection and performance that were varied or held constant included: Tonnage rate, moisture content, air flow rate through the drier, fuel oil rate to the burner, air flow rate to the burner, drum slope, drum diameter, drum length, and lifting flight design and arrangement. Some of the important results of this investigation are shown graphically in Figures 261 through 264. While these results were intended primarily for use in the asphaltic concrete industry, they may also be applied to similar rotary driers for other materials in other industries. Some of the conclusions drawn from this investigation are summarized and listed as follows.

1. Dust carryout increased proportionally to the square of the gas exhaust volume as the volume was increased in the same drum.

2. On driers of the same length with the same drum gas velocity and with other factors held constant, the maximum production capacity varied in direct ratio to drum cross-sectional area.

3. An increase in drum gas velocity permitted an increase in maximum production capacity, but on a less than direct ratio.

4. Thermal efficiency was a constant if the drier was properly balanced and operated, regardless of drier size, diameter, length, or drum gas velocity.

5. In a conventionally designed drum, a particle spent only a fraction of its time in the veil suspension while in the drum--usually not over 3 to 5 percent. For the remaining time, the particle cascaded at the bottom of the drum or rode up in the flight pocket.

6. Flights in a drum usually retarded rather than increased the flow of materials through the drums.

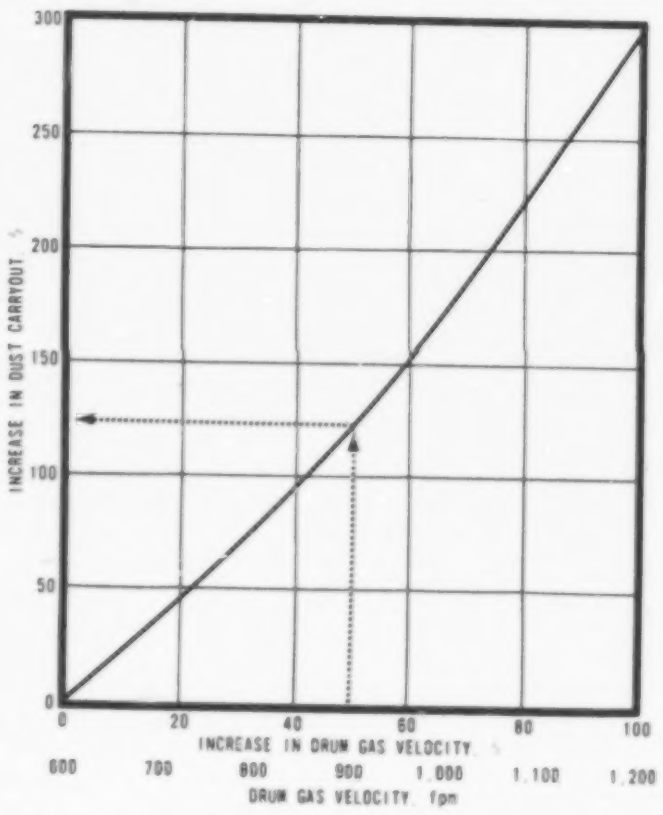


Figure 261. Dust carryout versus drum gas velocity. Example: An increase of 50% in gas velocity from 600 to 900 fpm increases dust carryout by 125% (Barber-Greene Company, 1960).

Flash Driers

In a flash drier, or pneumatic conveying drier, moisture is removed by dispersing the material to be dried in a hot gas zone followed by conveying at high velocities. The drier consists of a furnace or other source of hot gases, a device for dispersing the wet material in the gases, a duct through which the gases convey the material, and a collection system for removing the dry product from the gas stream. In the simplest type of system, a screw conveyor drops the material directly into a duct, as shown in Figure 265. Only free-flowing materials can be handled this way. Some recycled dry product often must be mixed with the wet material in order to achieve good dispersion.

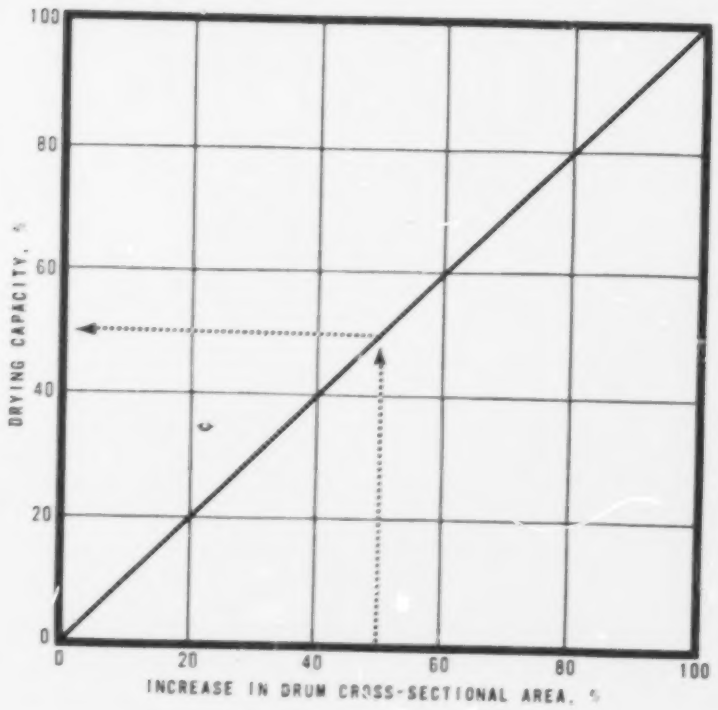


Figure 262. Drier production capacity versus drum cross-sectional area. Example: A 50% increase in cross-sectional area increases drying capacity by 50% (Barber-Greene Company, 1960).

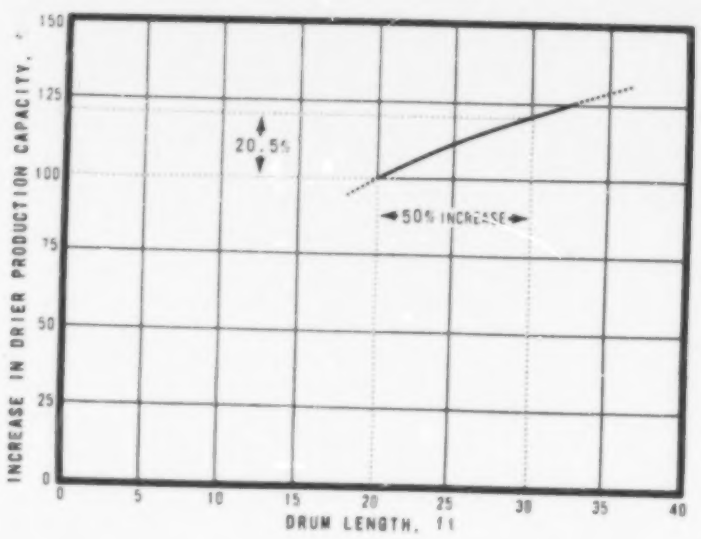


Figure 263. Drier production capacity versus drum length. Example: A 50% increase in drier length, from 20 to 30 feet, increases drying capacity by 20.5% (Barber-Greene Company, 1960).

A cage mill is often used as the dispersing device. Flash drying is often combined with fine grinding as shown by the system in Figure 266.

Spray Driers

A spray drier is a device in which atomized particles of a solution, slurry, or gel are dispersed in a hot gas zone (Marshall and Friedman, 1950). The drier consists of a drying chamber, a source of hot gases, a device for atomizing the feed, and a means of separating the dry product from the exhaust gases. The last item is the one of concern here.

Atomization is achieved by three devices: Centrifugal discs, high-pressure nozzles, or two-fluid nozzles. Centrifugal discs rotate at high speed in a horizontal plane. The liquid is fed to the center and discharged at the periphery as a fine spray. High-pressure nozzles contain a very small orifice through which the liquid is forced at a very high pressure. Particle size is controlled by amount of pressure and size of orifice. Two-fluid nozzles use air or steam under moderate pressure to atomize the liquid. The fluids are fed by separate lines to the nozzle where they impinge in a variety of different ways to produce a spray.

The hot gases for spray driers are usually obtained from a direct-fired air heater using natural gas or fuel oil. In some cases waste flue gas from a boiler is used. When carbon dioxide must be excluded from the drying atmosphere, steam coils are used to heat the air.

The drying chamber in some spray driers is shaped like a cyclone separator and serves as a primary product collector. In other types the drying chamber acts as a settling chamber to collect the bulk of the product. Sometimes, all the product is carried out in the exhaust gases and collected in an external product collector. The product collector is nearly always a cyclone separator followed by a secondary collector where needed.

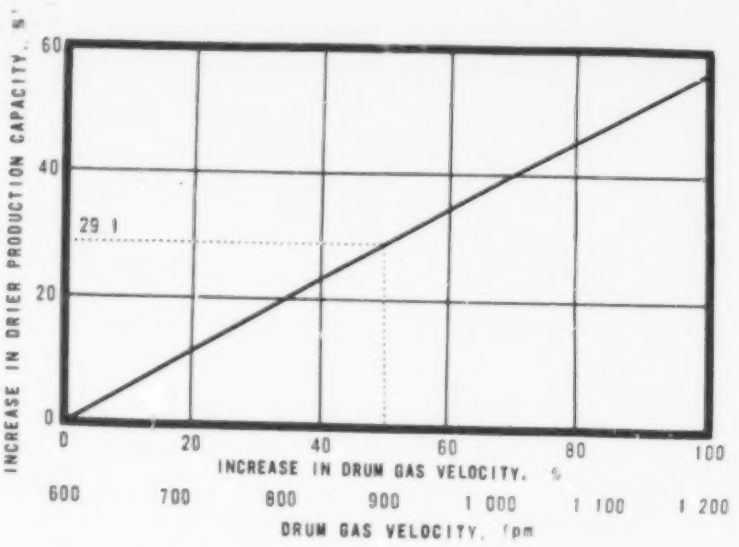


Figure 264. Drier production capacity versus drum gas velocity. Example: An increase of 50% in gas velocity, from 600 to 900 fpm, increases drying capacity by 29.1% (Barber-Greene Company, 1960).

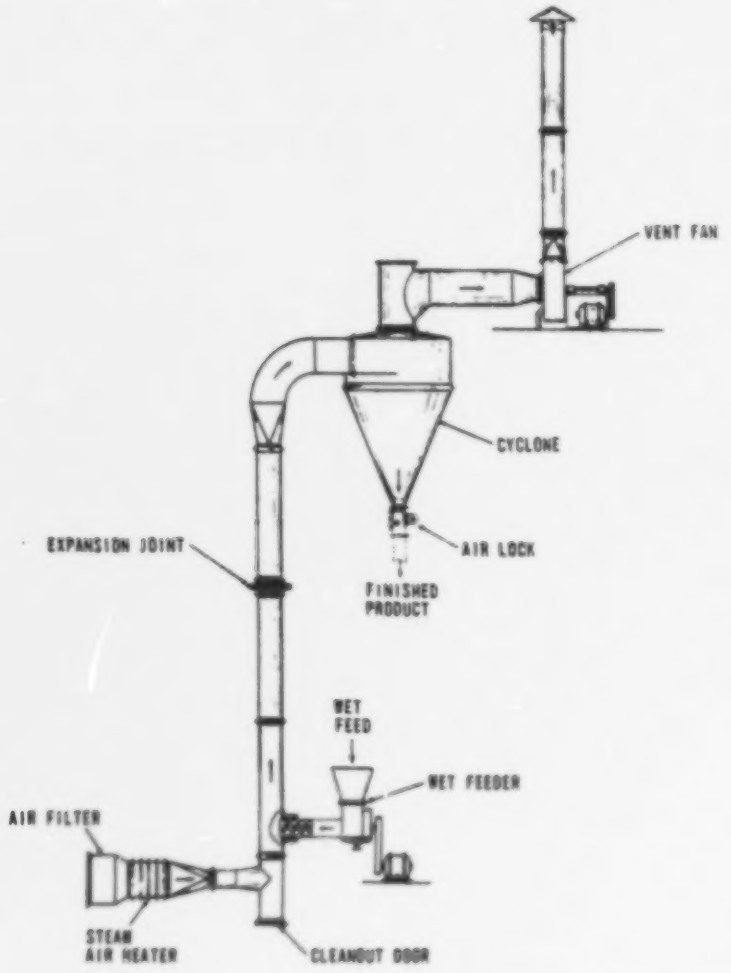


Figure 265. Simplest type of flash drying system (Combustion Engineering, Inc., Windsor, Conn.).

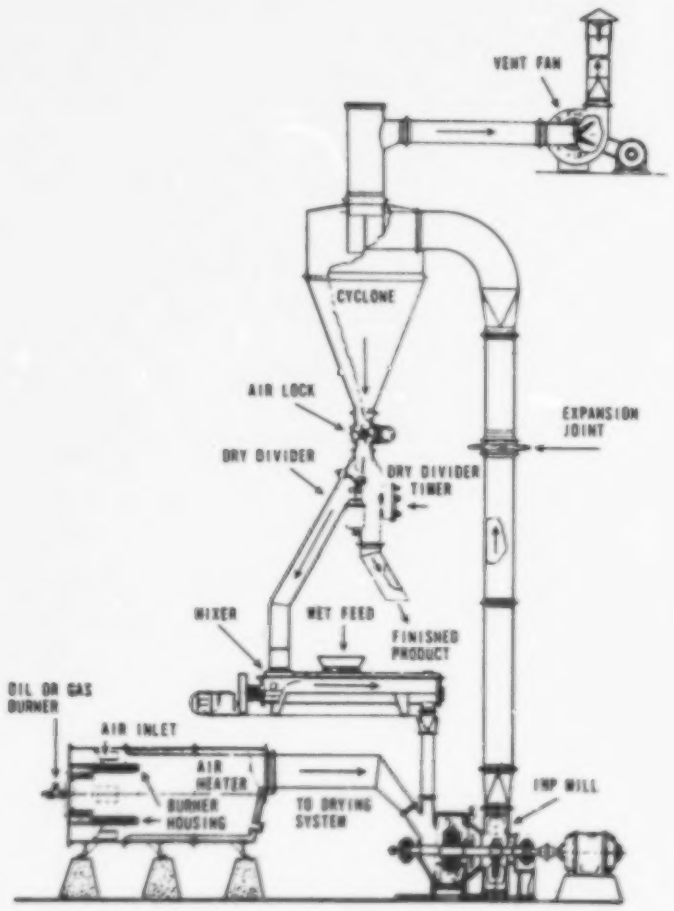


Figure 266. Flash drying combined with size reduction (Combustion Engineering, Inc., Windsor, Conn.).

Other Types of Driers

The following types of driers usually emit negligible amounts of dust. In some operations, however, organic vapors and mists may constitute a problem.

Tray and compartment driers consist of a chamber in which heated air circulates over the wet material until the material reaches the desired moisture content. Granular material, filter cakes, pastes, and slurries are placed in trays, which are put on stationary or movable racks, as shown in Figure 267. Other materials are stacked or hung on racks. The vertical turbodrier can be classified as a continuous tray drier. It consists of a vertical, cylindrical housing with circular trays mounted on a framework that slowly revolves. Material fed to the top tray is leveled by stationary knives and, after about seven-eighths of a revolution, is pushed through a slot to the tray below, where the procedure is repeated. Airflow across the trays is produced by fans mounted on a central shaft. Heating coils at the periphery of the housing heats the air as it is recirculated.

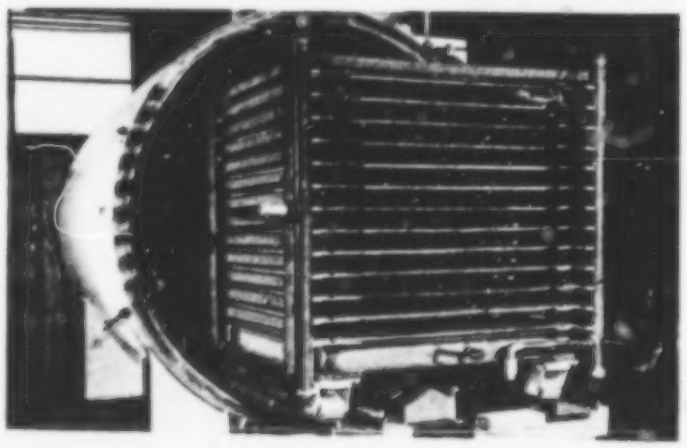


Figure 267. Tray drier (J.P. Devine Mfg. Company, Pittsburgh, Pa.).

Agitated pan driers consist of a bowl-shaped vessel, steam-jacketed on the bottom and part way up the sides, with stirrer or scraper blades to keep the material agitated. The top may be open for atmospheric drying or provided with a cover for vacuum drying.

Rotary vacuum driers are of two types. One type consists of a stationary, jacketed cylinder mounted horizontally with agitator blades mounted on a central revolving shaft. Material is charged through a manhole at the top and discharged through a manhole at the bottom. Another type of vacuum rotary drier consists of a rotating, jacketed cylinder with vacuum applied through hollow trunnions.

THE AIR POLLUTION PROBLEM

Air contaminants that may be emitted from driers are dusts, vapors, smoke, and odors. The nature of the emissions is determined by the material being dried and by the operating conditions.

Dust can be a problem in any drier in which the material is agitated or stirred during the drying process. Drier types that can be prolific dust producers are direct-fired rotary driers, flash driers, and spray driers. Types that produce less dust are indirect-heated rotary driers, pan driers, and cylinder driers. Other types that may emit no dust include tray driers, sheeting driers, and driers for products such as lumber, bricks, ceramic ware, and so forth.

When an organic liquid is to be removed from a material, the emissions may include vapors, mists, odors, and smoke.

HOODING AND VENTILATION REQUIREMENTS

Direct-fired rotary driers are usually equipped with an induced-draft fan or with a stack of sufficient height to provide draft for the combustion process. The ventilation requirement is equal to the volume of the products of combustion, plus vapors driven off from the product, plus sufficient excess to ensure an adequate indraft velocity through all openings.

Flash driers and spray driers have no ventilation requirement as such. The exhaust fan is usually placed at the product discharge end of the system, and the entire system is under negative pressure, which precludes emissions, except for the final collector.

AIR POLLUTION CONTROL EQUIPMENT

In general, three types of controls are used on driers: Dust collectors, condensers, and afterburners. The type of material being dried determines the kind of control device needed. Dust collectors are the most frequently used type since dust is usually the problem. All types of dust collectors are used, depending upon the amount and particle size of the dust emitted. Condensers are used when a material wet with an organic solvent is dried. Afterburners are used to control smoke, combustible particulate matter, vapors, and odors.

Dust Control

The types of dust collectors most commonly used on driers are cyclones, scrubbers, and baghouses. If there is only a negligible amount of dust in the effluent finer than 20 microns, a cyclone is an adequate collector; otherwise, it is not. Cyclones are extensively used ahead of scrubbers in order to collect product materials in the dry form. A baghouse is the best collector if the exit gases can be maintained above the dewpoint and the dust is not sticky. In some cases a scrubber is the only feasible control device.

The primary product collector for a flash drier is nearly always a cyclone separator. When fine materials are dried or when grinding is incorporated in the circuit, a baghouse following the cyclone is normally required, both to prevent excessive loss of product and to ensure control of air pollution. The size of the baghouse is determined by the volume of the drying and conveying gases. The bag material that can be used should be determined by the temperature at the baghouse. In some cases the temperature may be low enough to permit use of cotton or wool, but in most cases Dacron or Orlon is better.

Baghouses and scrubbers are used as secondary collectors for spray driers. A very efficient secondary collector is usually best in areas having a strict limitation on particulate emissions. The closeness of approach to the dewpoint determines the suitability of a baghouse. When the feed liquid is dilute and requires concentration, it can be used as the scrubbing liquid in a wet collector and thereby increase the concentration and recover the dust in the exhaust gases at the same time.

Drying With Solvent Recovery

When a liquid other than water is to be removed from a material, recovery of the solvent is frequently desirable in order to lower costs, prevent a safety hazard, and eliminate air pollution (Marshall and Friedman, 1950). The value of the solvent may require its recovery for economic operation. If the solvent is a toxic or flammable material, health and safety considerations may dictate its recovery.

Vacuum driers are well suited to recovery of solvent vapors. The vapors are removed under slight or high vacuum with only a small quantity of air, which is originally present or leaks into the system during operation. If dust is carried over, the vapors are drawn through a dust collector to prevent losses of product and fouling of condenser surfaces. The collector is usually a scrubber in order to preclude difficulties with condensed vapor. In some cases, where condensation at the collector can be prevented, bag filters are used.

From the dust collector the vapors usually pass through a surface condenser where the solvent is collected in a barometric leg or a tank kept at a low pressure. The gases leaving the condenser consist of the inert gases that have leaked in plus enough solvent vapor to form a saturated mixture at the condenser's temperature and pressure.

Vacuum pumps, both rotary and reciprocating, and steam jets are used as vacuum sources. The vacuum at the condenser must be adjusted so that the boiling point of the solvent is well above the temperature attainable in the condenser. Otherwise, solvent recovery will be poor or will be reduced to zero if the boiling point is brought down to the condenser temperature. Sometimes, recovery can be improved by placing an additional small condenser on the outlet of the vacuum pump.

Drying with solvent recovery can be accomplished with direct drying under certain circumstances. Heated air or inert gases are used and the vaporized solvent is recovered in a condenser. The noncondensable gases are usually recirculated through a heater. If air is used, the solvent concentration must be kept well below the lower explosive limit. Since the amount of inflammable solvents that could be condensed at these concentrations and at feasible condenser temperatures is negligible, this method is restricted to noninflammable solvents such as perchlorethylene, carbon tetrachloride, and so forth. An inert gas atmosphere is needed for recovering inflammable solvents from direct driers. Since the cost of maintaining an inert atmosphere is considerable, this method is not widely used.

Smoke and Odor Emissions

Direct-fired rotary driers, when drying certain organic materials, sometimes emit smoke and odors. Cannery or brewery wastes used to produce fertilizer or animal food are examples. Most of these driers can be operated without excessive air-contaminating emissions under the proper conditions. If feed rate and temperature are properly adjusted, a dry product results without any localized overheating. If, however, the feed rate is excessive, the required higher temperature causes localized overheating and partial decomposition of the product, resulting in the emission of smoke and odors. Scrubbers are usually used to control dust emissions from these driers, but are not adequate for controlling smoke and odors.

Another drying operation that emits smoke is the removal of cutting oils from metal turnings and chips. This operation nearly always produces enough smoke to violate smoke prohibitions. An afterburner is the only feasible control. A temperature of at least 1,200°F is required in the afterburner for complete smoke control. Temperature control in the drier is rather critical. The temperature must be high enough to vaporize the oil but not high enough to cause it to burn in the drier since this would cause the chips to melt or oxidize. A mechanical feeder is almost a necessity to secure good control of the operation. Hand feeding nearly always results in poor temperature regulation and in undried and burned chips.

WOODWORKING EQUIPMENT

Woodworking machines produce large quantities of waste sawdust, chips, and shavings that must be removed from the equipment site. For this purpose, exhaust systems are constructed that also alleviate conditions tending to impair health of operating personnel, collect wastes that may have a resale value, and reduce fire hazards. The use of an exhaust system, however, requires a dust collector of some type to prevent an air pollution problem.

EXHAUST SYSTEMS

Exhaust systems are used with many types of woodworking machines capable of producing appreciable sawdust, chips, or shavings by drilling, carving, cutting, routing, turning, sawing, grinding, shredding, planing, or sanding wood. Machines include ripsaws, bandsaws, resaws, trim saws, mitre saws, panel saws, out-off saws, matchers, stickers, grinders, moulders, planers, jointers, spindle sanders, edge sanders, tenoners, mortisers, wood hogs (hammer mills), groovers, borers, dovetailers, and others. Exhaust systems serving wood hogs might more properly be termed pneumatic conveyors. In practice, however, wood hogs are most often found connected to exhaust systems that also serve other woodworking machines.

Exhaust systems serving various woodworking machinery are most frequently used at lumber mills, furniture manufacturers, planing mills, furniture-refinishing shops, model shops, maintenance shops, cabinet shops, sash and door manufacturers, and carpenter shops. Many of the larger systems handle several tons of waste products per day. One of the largest in the Los Angeles area burns 15 to 20 tons per day in a multiple-chamber incinerator. One ton of waste sawdust, chips, and shavings occupies approximately 150 to 200 cubic feet of space.

Construction of Exhaust Systems

A typical woodworking exhaust system consists of hoods for the pickup of wood dust and chips at the machines, ductwork, a collection device (usually a cyclone), a storage bin, and a fan blower to supply air for conveying purposes. Almost all exhaust systems are constructed of galvanized sheet metal.

THE AIR POLLUTION PROBLEM

Woodworking exhaust systems are somewhat unique in that they are almost always equipped with air pollution control devices. If they were not so equipped, the entrained sawdust would result in excessive opacities and dust loadings in exit gases and could easily cause a local nuisance. Air contaminant emissions from systems such as these are functions of the particular dust encountered and the particular control device employed. The dust particles are not excessively small in most systems, and elaborate devices are not usually required.

Particles emitted by woodworking machines vary in size from less than 1 micron to chips and curls several inches long. Hammer mill-type wood hogs emit particles running the complete size range, while sanders generate only very small dust particles. Wood waste particles from most other machines are of larger size and greater uniformity, seldom less than 10 microns. Other factors determining particle size are the type of wood processed and the sharpness of the cutting tool. Hardwoods tend to splinter and break, yielding smaller particles than soft woods do, which tend to tear and shred. A dull cutting tool increases tearing and shredding and produces larger particle sizes.

Generally, the configuration of waste particles is of little importance. There are, however, instances where toothpick-like splinters and curls have presented difficulties in collection and storage and in the emptying of storage bins.

HOODING AND VENTILATION REQUIREMENTS

Sawdust weighs from 7 to 15 pounds per cubic foot. The minimum recommended air volume for each pound of wood waste to be conveyed is 45 cubic feet or, expressed differently, is 1,500 cfm per ton-hour of waste. In actual practice the air volume is usually much higher because of exhaust velocity requirements.

Velocities recommended for conveying this material range from 3,500 to 4,500 fpm, with most ducts sized to give a velocity of 4,000 fpm. In practice, velocities of from 2,000 to 6,000 fpm are encountered.

Table 108 lists recommended exhaust volumes for average-sized woodworking machines. In each case the duct is sized to give a conveying velocity of 4,000 fpm. Some modern high-speed or extra large machines produce such large volumes of wastes that greater exhaust volumes must be used. Similarly, some small machines of the home woodshop or bench type may not require as large a volume as that recommended.

Hooding devices vary somewhat, depending upon the type of woodworking machine, and are of standard design throughout the industry. In most cases, the hoods are merely scooped openings that catch the wood waste as it is thrown from the saws or blades of the machine. In design practice, no problems should be encountered if air volumes are chosen from those shown in Table 108, and if hoods are shaped to cover the area assumed by the thrown particles. Locating the hood as close to the saw or blade as possible is advisable.

AIR POLLUTION CONTROL EQUIPMENT

The simple cyclone separator is the most common device used for collecting wood dust and chips from woodworking exhaust systems. For these exhaust systems, cyclones outnumber all other devices by a large margin. Properly designed cyclones have been found satisfactory for use with exhaust systems at cabinet shops, lumber yards, planing mills, model shops, and most other wood-processing plants.

Higher efficiency centrifugal collectors separate smaller particles, but these devices are not common to woodworking systems. The main advantage of simple cyclones over most other collection devices is simplicity of construction and ease of operation. They are relatively inexpensive, require little maintenance, and have only moderate power requirements.

The size and design of woodworking exhaust system cyclones varies with air volume and the type of wood waste being handled. Where fine sander dust predominates, cyclones should be of high-efficiency design with diameters not greater than 3 feet. Coarse sawdust, curls, and chips, such as are produced with ripsaws, moulders, and drills, can be effectively collected with low-efficiency cyclones up to 8 feet in diameter. Most woodworking exhaust systems are employed to collect a mixture of wood waste including both fine and coarse particles. The exhaust system designer must, therefore, carefully consider the quantities of each type wood waste that will be handled. The presence of appreciable percentages of coarse particles in most systems allows the use of low- and medium efficiency cyclones, in which the pressure drop does not normally exceed 2 inches of water column.

Baghouses are sometimes used with woodworking exhaust systems. Their use is relegated to those systems handling fine dusts such as wood flour or where small amounts of dust losses cannot be tolerated in the surrounding area. The efficiency of baghouses on woodworking exhaust systems is very high--99 percent or more. They can be used to filter particles as low as 1/10 micron in size. In some installations lower efficiency collectors such

Table 108. EXHAUST VOLUMES AND DUCT SIZES FOR WOODWORKING EQUIPMENT
(Committee on Industrial Ventilation, 1960)

	Exhaust volume, cfm		Duct diameter, in.	
	Bottom hood	Top hood	Bottom hood	Top hood
Self-feed table ripsaw:				
Saw diameter, in.				
Up to 16	440	350	4-1/2	4
Over 16	550	350	5	4
Self-feed, not on table	800	550	6	5
Gang ripsaws:				
Saw diameter, in.				
Up to 24	550	350	5	4
Over 24 up to 36	800	440	6	4-1/2
Over 36 up to 48	1,100	550	7	5
Over 48	1,400	550	8	5
ALL OTHER SAWS, including table saws, mitre saws, variety saws, and swing saws.				
Saw diameter, in.				
Up to 16	350		4	
Over 16 up to 24	440		4-1/2	
Over 24	550		5	
Variety saw with Dado head	550		5	
Vertical belt sanders: (rear belt and both pulleys enclosed) and top run horizontal belt sanders:				
Belt width, in.				
Up to 6	440		4-1/2	
Over 6 up to 9	550		5	
Over 9 up to 14	800		6	
Over 14	1,100		7	
Swing arm sander:	440		4-1/2	
Disc sanders: diameter, in.				
Up to 12	350		4	
Over 12 up to 18	440		4-1/2	
Over 18 up to 25	550		5	
Over 26 up to 32, 2 pipes	350 each		4 each	
Over 32 up to 38, 2 pipes	350 and 550		4 and 5	
Over 38 up to 48, 3 pipes	550		5	
	350		4	
Triple-drum sanders:				
Length, in.				
Less than 30	1,100		7	
Over 30 up to 36	1,400		8	
Over 36 up to 42	1,800		9	
Over 42 up to 48	2,200		10	
Over 48	3,100		12	
Horizontal belt sanders:				
Belt width, in.				
Where bottom run of belt is used				
Up to 6	440	350	4-1/2	4
Over 6 up to 9	550	350	5	4
Over 9 up to 14	800	440	6	4-1/2
Over 14	1,100	550	7	5

	Exhaust volume, cfm		Duct diameter, in.	
	Down run	Up run	Down run	Up run
Band saws and band resaws:				
Blade width, in.				
Up to 2	350	350	4	4
Over 2 up to 3	550	350	5	4
Over 3 up to 4	800	550	6	5
Over 4 up to 6	1,100	550	7	5
Over 6 up to 8	1,400	550	8	5
Jointers:				
Knife length, in.				
Up to 6	350		4	
Over 6 up to 12	440		4-1/2	
Over 12 up to 20	550		5	
Over 20	600		6	
Single planers:				
Knife length, in.				
Up to 20	500		5	
Over 20 up to 26	800		6	
Over 26 up to 36	1,100		7	
Over 36	1,400		8	

	Bottom hood	Top hood	Bottom hood	Top hood
Double planers:				
Knife length, in.				
Up to 20	550	550	5	5
Over 20 up to 26	550	800	5	6
Over 26 up to 36	800	1,100	6	7
Over 36	1,100	1,100	7	7

	Bottom hood	Top hood	Right hood	Left hood	Bottom hood	Top hood	Right hood	Left hood
Molders, matchers, and sizers:								
Sizes, in.								
Up to 7	440	550	350	350	4-1/2	5	4	4
Over 7 up to 12	550	800	440	440	5	6	4-12	4-1/2
Over 12 up to 18	800	1,100	550	550	6	7	5	5
Over 18 up to 24	1,100	1,400	800	800	7	8	6	6
Over 24	1,400	1,770	1,100	1,100	8	9	7	7

Sash stickers	550	5
Woodshapers	440 to 1,400	4-1/2 to 8
Tenoner	See moulder	
Automatic lathe	800 to 5,000	6 to 15
Forming lathe	350 to 1,400	4 to 8
Chain mortise	350	4
Dowel machine	350 to 800	4 to 6
Panel raiser	550	4-1/2
Dovetail and lock corner	550 to 800	4-1/2 to 6
Pulley pockets	550	4-1/2
Pulley stile	550	4-1/2
Glue jointer	800	6
Gainer	350 to 1,400	4 to 8
Router	350 to 800	4 to 6
Hogs		
Up to 12 in. wide	1,400	8
Over 12 in. wide	3,100	12
Floorsweep (6 to 8 in. dia)	800 to 1,400	6 to 8

as cyclones and impingement traps are installed upstream to remove the bulk of entrained particulates before final filtering in a baghouse. Filtering velocities of 3 fpm are satisfactory.

Disposal of Collected Wastes

Wood dust and chips collected with exhaust systems must be disposed of since they present a storage problem and a fire hazard. Very often a profit can be realized from this waste material. Wood wastes can be used productively for things such as:

1. Plastics bulking agent for products such as plastic wood, masonite, and so forth;

2. pressed woods such as firewood, fiberboard, Firtex, and others;

3. soil additives;

4. smokehouse fuel--hardwood sawdust is burned to produce smoke in the processing of bacon, ham, pastrami, and so forth;

5. floor sweep--sawdust with and without oil is spread on floors before they are swept to help hold dust particles;

6. wood filler--sawdust can be mixed with water resins and other liquids and used as wood filler;

7. floor cover in butcher shops, restaurants, and so forth;

8. waste heat boilers--heat can be recovered from incinerator flue gases to generate steam, hot water, and so forth.

When no productive disposal method can be used, wood waste is destroyed or removed in the most convenient manner. Wood dust and chips collected by the woodworking exhaust systems can be destroyed smokelessly by burning in a multiple-chamber incinerator. Single-chamber incinerators, for example, silo-type or teepee-type incinerators, cannot be controlled adequately for satisfactory air pollution abatement. Generally, wood waste is conveyed from the collection device to the incinerator by a pneumatic or a mechanical conveying system. In areas where the services of a cut-and-cover dump are available, disposal by incineration is usually not economical.

RUBBER-COMPOUNDING EQUIPMENT

INTRODUCTION

Rubber in its raw state is too plastic for most commercial applications, and its use is, therefore, limited to a few items such as crepe rubber shoe soles, rubber cements, adhesives, and so forth (Shreve, 1945). Through a curing process termed vulcanizing, raw rubber can be made to lose plasticity and gain elasticity. By compounding the raw rubber with various types and amounts of additives before the vulcanizing, tensile strength, abrasion resistance, resiliency, and other desirable properties can be imparted to the rubber. The proportions and types of additives (including vulcanizing agents) compounded into the raw rubber, and the vulcanizing temperature, pressure, and time are varied in accordance with the properties desired in the final product. After the rubber is compounded, it is formed into the desired shape and then cured at the required temperature. In the forming steps, large amounts of organic solvents are often used in the form of rubber adhesives. Since the solvent emissions are not controlled, they will not be discussed further in this section.

Additives Employed in Rubber Compounding

Types of additives that are compounded into the rubber may be classified as vulcanizing agents, vulcanizing accelerators, accelerator activators, retarders, antioxidants, pigments, plasticizers and softeners, and fillers. Examples of additives that may be encountered in rubber compounding are tabulated by type (Kirk and Othmer, 1947).

1. Vulcanizing agents. Sulfur was originally considered essential to vulcanizing and, though vulcanizing is now possible without it, sulfur or sulfur compounds such as sulfur monochloride are widely used. Selenium and tellurium can also be used for this purpose.

2. Vulcanizing accelerators. Aldehyde-amines, guanidines, and thiuram sulfides are used to decrease the time and temperature required for vulcanization.

3. Accelerator activators. Zinc oxide, stearic acid, litharge, magnesium oxide, and amines suppiement the accelerators and, in addition, modify finished product characteristics, for example, they increase the modules of elasticity.

4. Retarders. Salicylic acid, benzoic acid, and phthalic anhydride retard the rate of vulcanizing.

5. Antioxidants. Several organic compounds, mostly alkylated amines, are used to retard deterioration of the rubber caused by oxidation and improve aging and flexing ability.

6. Pigments. Carbon black, zinc oxide, magnesium carbonate, and certain clays are used to increase tensile strength, abrasion resistance, and tear resistance. Iron oxide, titanium oxide, and organic dyestuffs are used to color the rubber.

7. Plasticizers and softeners. Resins, vegetable and mineral oils, and waxes are used to improve resiliency, flexibility, and mixing and processing characteristics.

8. Fillers. Whiting, slate flour, barytes, and some of the pigments previously mentioned are used to improve processing properties and lower the cost of the finished product.

In the compounding of blends, the accelerators are added first to the mass of raw rubber being milled or mixed. Then a portion of the plasticizers (if present in the blend recipe) are added, followed by the reinforcing pigments, the remainder of the plasticizers, the antioxidants, and any inert fillers or coloring agents. The vulcanizing agent is always introduced as the last ingredient.

In order to be effective in imparting various chosen characteristics, all additives employed in a blend must be homogeneously dispersed throughout the blend. The two most commonly employed pieces of equipment for blending rubber and additives are rubber mills and Banbury mixers.

A typical rubber mill is shown in Figure 268. The two rolls rotate toward each other at different speeds, creating a shearing and mixing action. Raw rubber is placed in the mill, and the additives are introduced, generally one or two components at a time. Additives may be finely divided solids or liquids.

Another device commonly used for compounding rubber stock is the Banbury mixer. Figure 269 shows cross-sections of two typical Banbury mixers. Each consists of a completely enclosed mixing chamber in which two spiral-shaped rotors, revolving in opposite directions and at different speeds, operate to keep the stock in constant circulation. A ridge between the two cylindrical chamber sections forces intermixing, and the close tolerances of the rotors with the chamber walls results in a shearing action. A floating weight in the feed neck confines the batch within the sphere of mixing. This combination of forces produces an ideally homogeneous batch.

THE AIR POLLUTION PROBLEM

Sources of air pollution from the mills are (1) finely ground dusts introduced as additives, (2) fumes generated by mechanical working of the batch by the mill rollers, (3) oil mists from liquid additives, and (4) odors. A major source of air pollution from rubber mills occurs when the finely divided dusts are introduced into the batch. Opacity of the resultant dust cloud depends upon the character, density, and particle size of the additive. Opacity generally ranges from 5 to 50 percent, persisting from a few seconds to several minutes.

Uncontrolled emissions vary from a negligible amount to about 1 pound per hour, depending upon the size of the mill, the size of the batch, and the composition of the mix. Emissions average approximately 0.5 pound per hour. Solvent vapors emanating from the mix are ordinarily uncontrolled and enter the atmosphere.

Introduction of ingredients into a Banbury mixer is effected through the feed hopper. It is at this point, during charging, that air contaminants may enter the atmosphere. Emissions are similar to those from the mills. In general, most of the dry ingredients are added at the Banbury mixer, carbon black being the most troublesome.

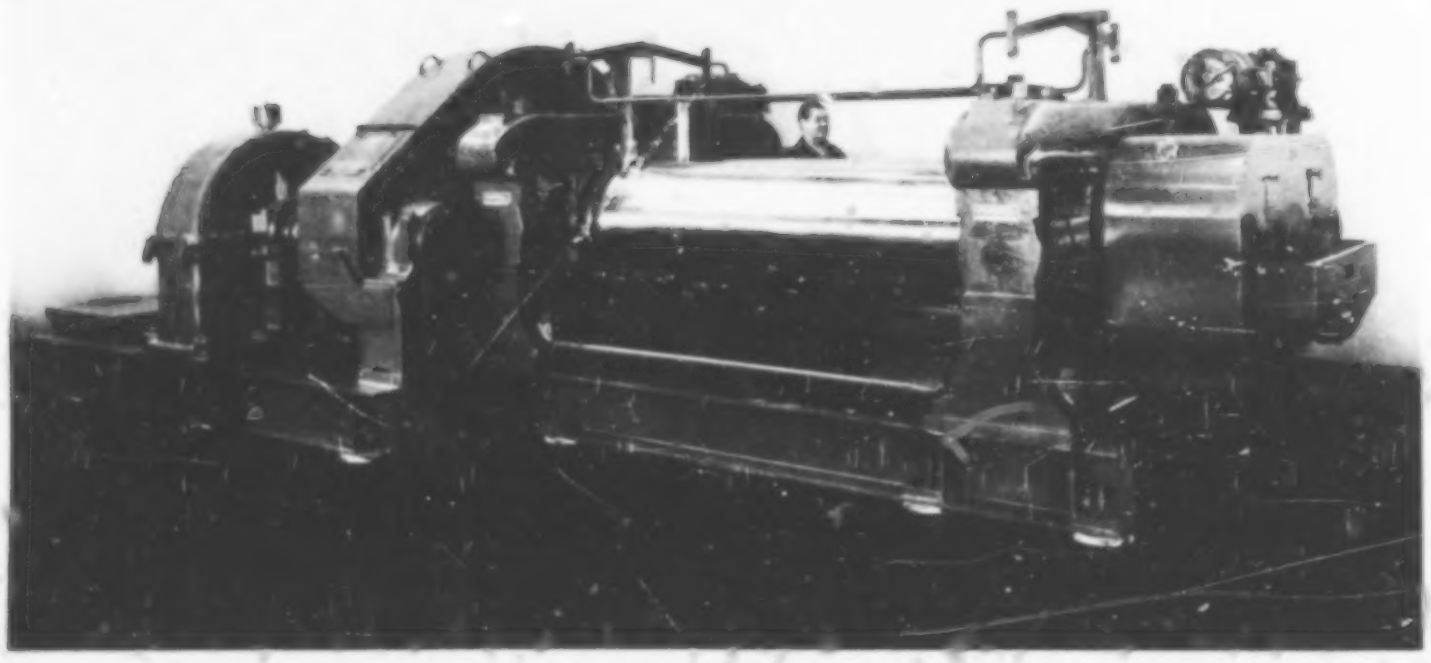
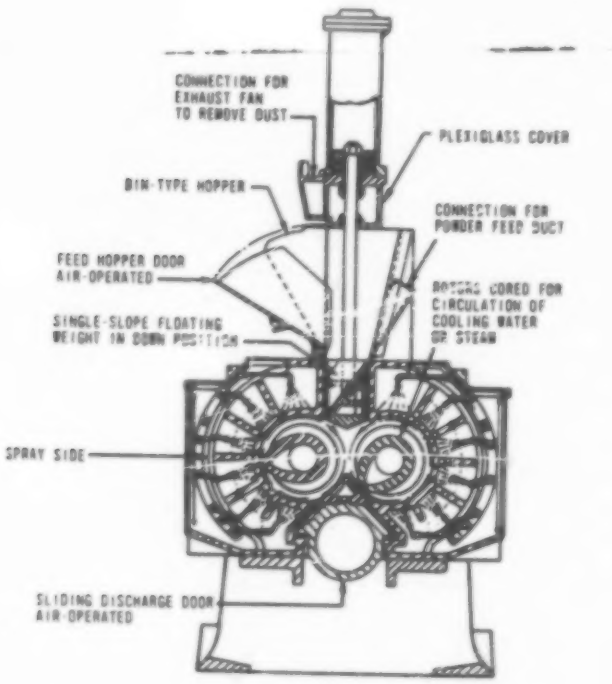


Figure 268. Rubber mill (Farrel Corporation, Ansonia, Conn.).


CONNECTION FOR EXHAUST FAN TO REMOVE DUST
PLEXIGLASS COVER
BIN-TYPE HOPPER
CONNECTION FOR POWDER FEED DUCT
FEED HOPPER DOOR AIR-OPERATED
ROTORS CORED FOR CIRCULATION OF COOLING WATER OR STEAM
SINGLE-SLOPE FLOATING WEIGHT IN DOWN POSITION
SPRAY SIDE
SLIDING DISCHARGE DOOR AIR-OPERATED

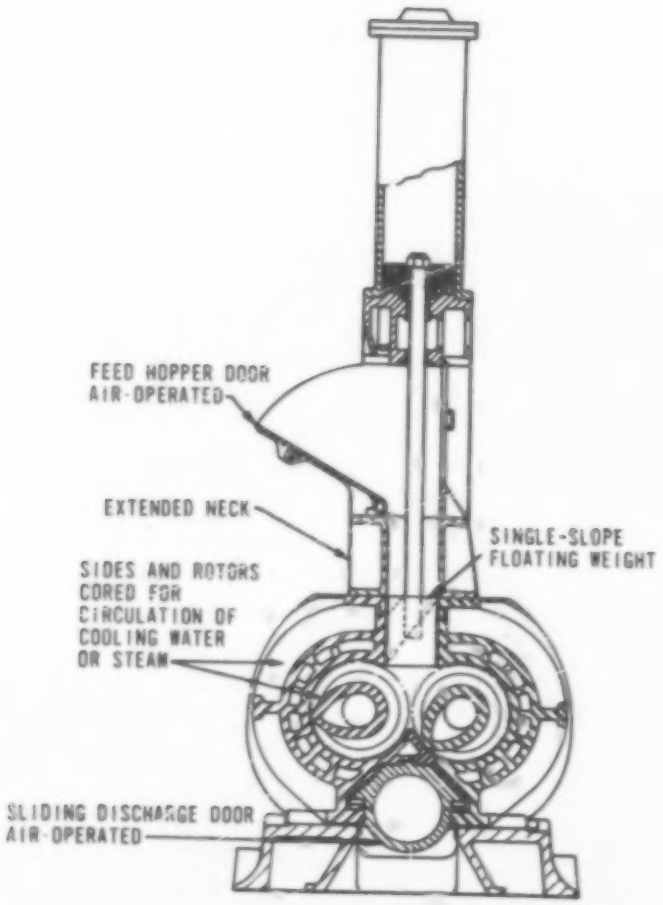

FEED HOPPER DOOR AIR-OPERATED
EXTENDED NECK
SINGLE-SLOPE FLOATING WEIGHT
SIDES AND ROTORS CORED FOR CIRCULATION OF COOLING WATER OR STEAM
SLIDING DISCHARGE DOOR AIR-OPERATED

Figure 269. Two models of Banbury mixers (Farrel Corporation, Ansonia, Conn.).

HOODING AND VENTILATION REQUIREMENTS

Generally, rubber mills are provided with hoods, as shown in Figure 270. The primary purpose of a hood is to carry away heat generated by the mechanical mixing action. As a secondary consideration, the exhaust hood removes dust, fumes, and mists emitted from the rolls. Sufficient volume should be exhausted to give an indraft velocity of 100 fpm through the open face of the enclosure. Figure 269 shows the exhaust provisions supplied with a standard Banbury mixer. If an unusual dust problem is encountered, supplementary hooding can be added The minimum required exhaust volume is equal to 200 cfm per square foot of mixer charging opening.

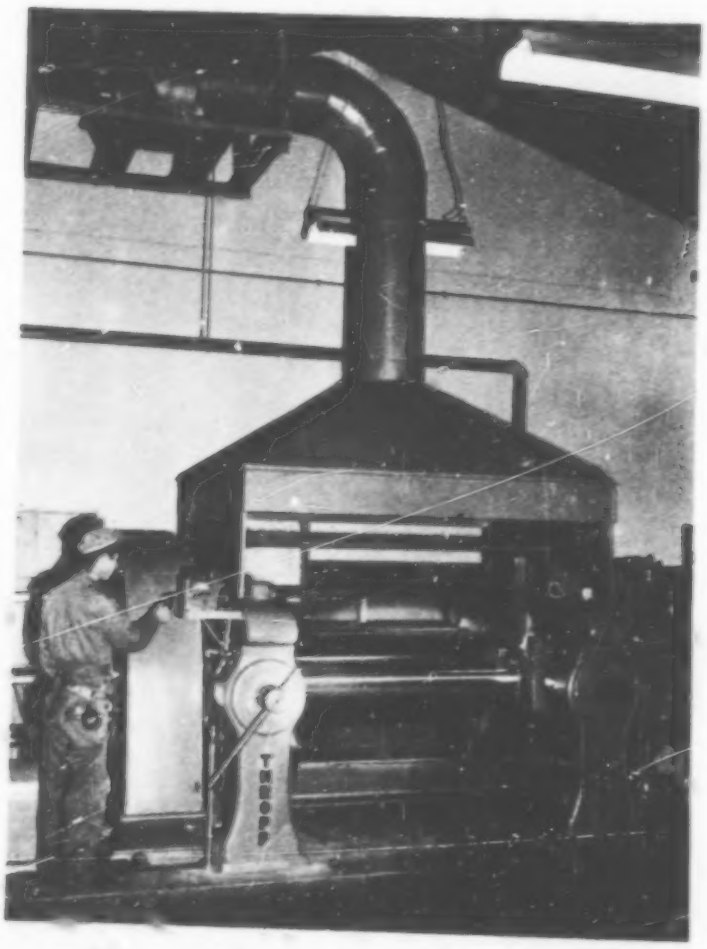


Figure 270. Rubber mill with exhaust hood (National Seal Division, Federal-Mogul-Bower Bearings, Inc., Downey, Calif.).

AIR POLLUTION CONTROL EQUIPMENT

In general, emissions from Banbury mixers and rubber mills are in a finely divided form and smaller than 15 microns. Inertial separators are not, therefore, effective control devices for this service. The most common control device employed

is the baghouse; a well-designed baghouse can be operated with 98 to 99.5 percent efficiency.

Standard cotton sateen bags are adequate at a filtering velocity of 3 fpm. In some cases scrubbers have also proved satisfactory and advantageous in scrubbing out some oil vapors and oil mists that may be present in some blends.

ASPHALT ROOFING FELT SATURATORS

Asphalt saturators are used to prepare asphalt-saturated felt in the manufacture of roofing paper and roofing shingles. The roofings are made by impregnating a vegetable felt base with asphalt derived from petroleum. The felt is made from fibrous vegetable matter and generally contains 5 to 10 percent water. The asphalts, known in the industry as saturants, are derived as still bottoms from petroleum crude oil, and are semisolids with softening points of 100° to 180°F.

DESCRIPTION AND OPERATION

Asphalt-saturated felt is manufactured in high-speed, continuous-operating machines, referred to as asphalt saturators. The asphalt saturator consists of a dry looper, an asphalt spray section, a saturating tank, and a wet looper. The felt is continuously fed from rolls into the dry looper where it is arranged over rollers into a series of vertical loops used as live storage in the process to permit maintenance of feed at a uniform rate to the saturating process during roll changes. The liquid asphalt at 400° to 450°F may then be sprayed on one side of the felt. This spray of hot asphalt drives moisture in the felt out the unsprayed side and prevents the moisture from forming blisters when the felt is saturated. After being sprayed, the felt passes through a tank of molten asphalt that saturates the felt. The saturated felt then enters the wet looper where the material is arranged over another set of rollers into long, vertical loops to permit cooling of the asphalt. The web of saturated felt is then rolled up from the discharge end of the wet looper for use as roofing felt or building paper, or a small quantity of bituminous material and mica schist or rock granules are applied to the surface to make composition roofing paper and shingles. Figure 271 is a schematic drawing of an asphalt roofing saturator.

THE AIR POLLUTION PROBLEM

Asphalt is generally applied to the felt at 400° to 450°F. This relatively high temperature causes the lower boiling components of the asphalt to vaporize. In addition, moisture from the felt vaporizes in the hot asphalt, resulting in steam distillation of the asphalt. These two vaporization mechanisms result in the creation of vaporous as well as particulate air contaminants, the latter being in the form of a highly opaque mist when the saturator is in operation. When felt is not being processed, the rate of air contaminant emissions decreases somewhat, but the opacity of the mist is usually well above 50 percent over the saturation tank. Figure 272 shows the mist emissions at the asphalt saturator tank. Additional vapors and mists are emitted from the saturated felt in the wet looper. The mass emission rate is a function of felt feed rate, felt moisture content, number of sprays used, and asphalt temperature, all of which are highly variable. It has been found, however, that the total contaminant emission rate is about 20 to 70 pounds per hour.

HOODING AND VENTILATION REQUIREMENTS

The points of air contaminant emission are the asphalt presaturator sprays, the saturator tank, the wet looper. Hoods for collecting the emissions should be installed so that there is a single continuous enclosure around the points of emission, extending down to the floor. Since operating personnel must have access to the saturator for operating adjustments, doorways or other provisions for entrance in the hood must usually be supplied. These should be kept as small as possible. In addition, openings in the hoods must be provided for the entrance of felt and exit of the saturated material. These openings should be as close to the floor as possible. Experience indicates that a minimum indraft velocity of 200 fpm is required at all hood openings. Air volumes handled by the exhaust system vary with hood design and saturator size but are about 10,000 to 20,000 scfm. Figures 273 and 274 illustrate hooding devices for an asphalt roofing saturator.

AIR POLLUTION CONTROL EQUIPMENT

The large volume of air required in controlling the saturator equipment generally makes incineration impractical. Baghouses, spray scrubbers, and two-stage electrical precipitators have been used as air pollution control equipment for asphalt saturators. Although more expensive in first cost, electrical precipitators are the most efficient and probably the most practical control device.

Low-Voltage Electrical Precipitators

The low-voltage, or two-stage, electrical precipitator preceded by a spray scrubber as a precleaner gives relatively high collection efficiency as well as a substantial reduction in the opacity of the saturator effluent. Figures 275 and 276 show equipment of this type. Table 109 shows the test results on a scrubber precleaner followed by a two-stage precipitator.

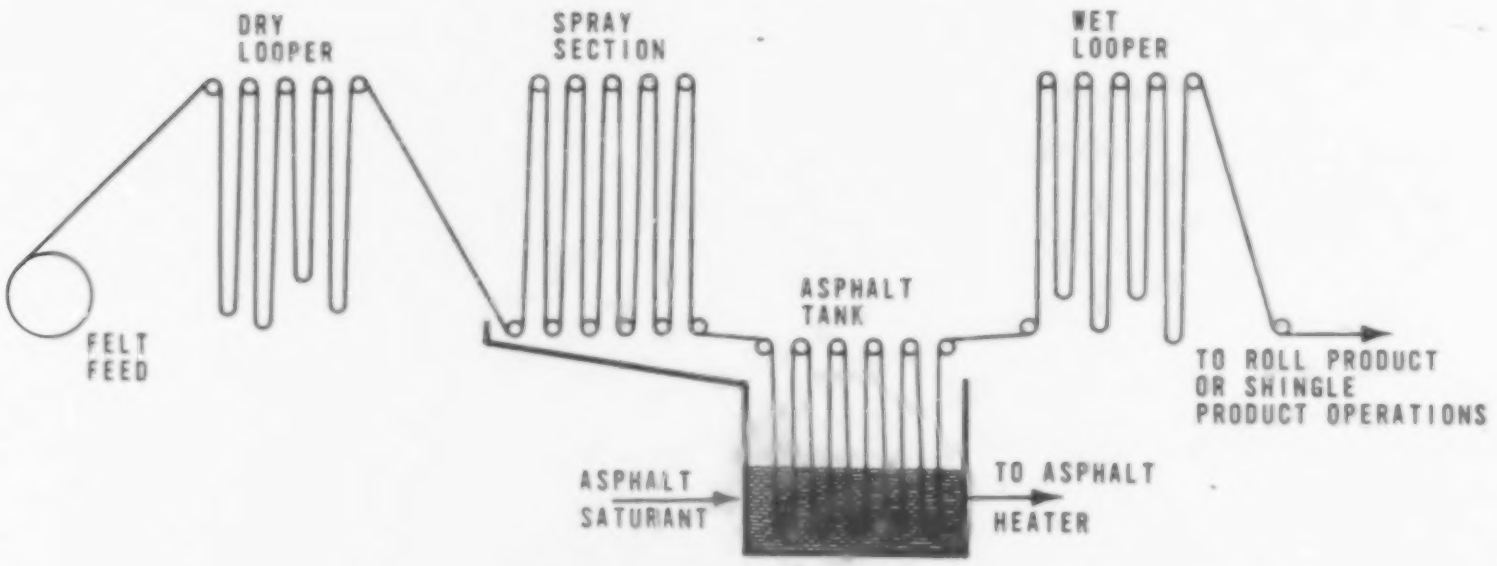


Figure 271. Schematic drawing of an asphalt roofing felt saturator.

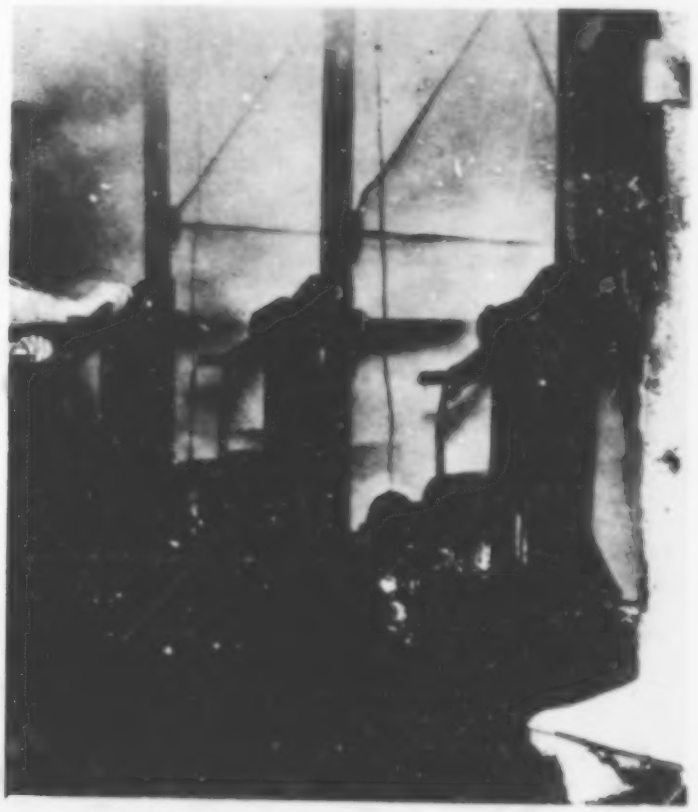


Figure 272. Emissions from asphalt saturator tank (Lloyd A. Fry Roofing Company, Los Angeles, Calif.).

Precleaners are usually wet collectors used to decrease the amount of oil mist handled by the precipitator. The precleaner removes particles more than 1 micron in diameter. Simple spray scrubbers or inertial scrubbers give adequate precleaner efficiency. The use of a precleaner causes evaporation of water into the warm airstream, accompanied by cooling of the airstream. The result is that the humidity at the lower temperature approaches saturation, and water condensation in the precipitator is a possibility.

Design Considerations for Electrical Precipitators

The design parameters of electrical precipitators controlling asphalt saturators are particularly critical since many particles to be removed are less than 1 micron in diameter. Particular attention must be directed to air distribution within the precipitator and to temperature drop across the unit.

Examination of the theory of electrical precipitators indicates that the time a contaminant particle remains within the conveying and collector fields has significant bearing on the precipitator's efficiency. Because the actual time in the electrical field is somewhat inconvenient to calculate, this parameter is usually expressed in terms of superficial velocity, which is based upon the overall area of the precipitator cells perpendicular to the direction of airflow. A typical low-voltage, two-stage precipitator has plate lengths of 8-1/2 inches in the direction of airflow and plates spaced 5/16 inch apart. The precipitator is operated with 10 to 15 kilovolts of ionizing voltage and 6 to 7 kilovolts of collector voltage. With a precipitator of this design, superficial velocities of less than 150 fpm usually provide adequate control of emissions from asphalt saturators.

Air distribution within the precipitator is important in this type of precipitator application. Poor air distribution leads to high velocities in some sections of the precipitator, yielding low overall col-

Table 109. EMISSIONS FROM A WATER SCRUBBER AND LOW-VOLTAGE, TWO-STAGE ELECTRICAL PRECIPITATOR VENTING AN ASPHALT SATURATOR

	Scrubber inlet	Precipitator inlet	Precipitator outlet
Volume, scfm	20,000	20,234	20,116
Temperature, °F	139	85	82
Emission rate,			
gr/scf	0.416	0.115	0.058
lb/scf	71.4	20	10
Water vapor, %	3.7	4.9	4.8
Collection efficiency	Scrubber, 71%	Precipitator, 50%	Overall, 86%

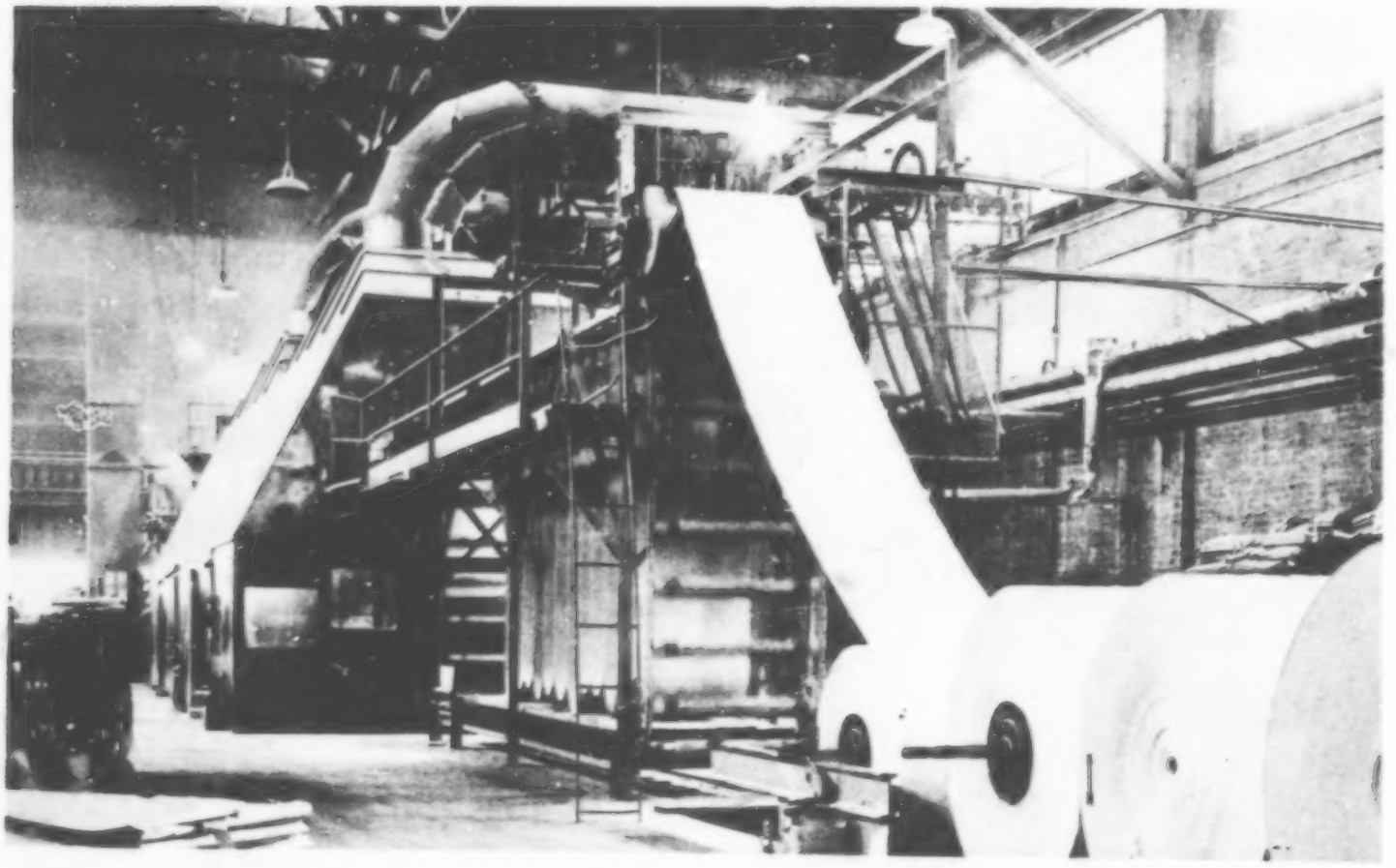


Figure 273. Asphalt saturator hood at felt feed (Lloyd A. Fry Roofing Company, Los Angeles, Calif.).

lector efficiency. Uneven air distribution can be caused by duct bends in the exhaust system just ahead of the precipitator inlet, abrupt transitions from inlet duct to precipitator housing, and buoyancy effects of warm air. The effect of the buoyancy of the warm air can be compensated for by the installation of perforated plates at the inlet and discharge sections of the precipitator. The transition section from the duct of the exhaust system to the housing of the precipitator should be carefully designed to provide for smooth and gradual changes in directions of airflow. Turbulence and poor velocity distribution due to duct bends in the exhaust system can be compensated for, in part, by the use of straightening vanes or of sectioned, adjustable, perforated plates.

The temperature drop across the precipitator is another important design consideration. The removal of water from the felt in the saturator as well as the water evaporated in the precleaner increases the water content of the air entering the

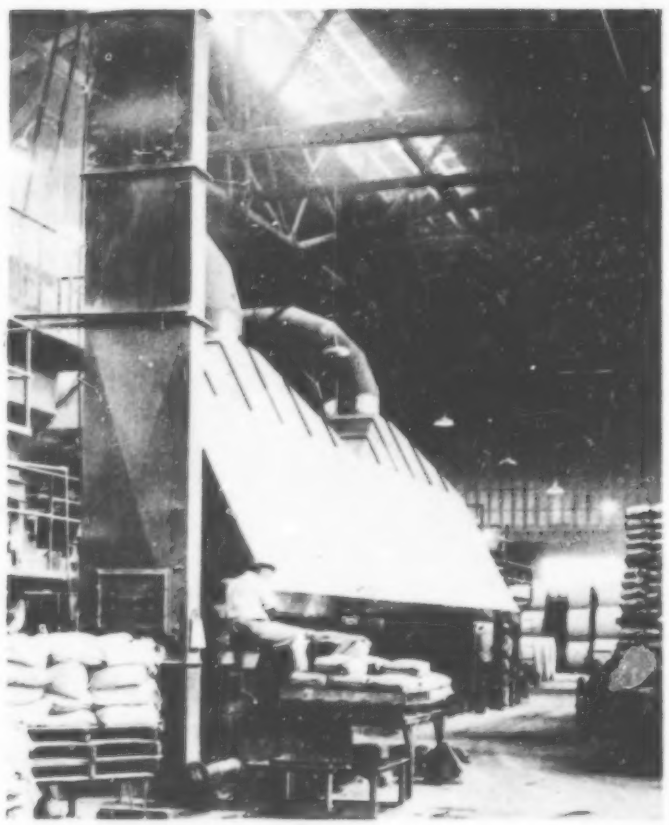


Figure 274. Asphalt saturator hood at saturator discharge (Lloyd A. Fry Roofing Company, Los Angeles, Calif.).

precipitator. The exit conditions of the scrubber may be such that the air may be near the dew point temperature, and the additional temperature drop in the precipitator of about 5°F may be sufficient to produce some condensation. The presence of water droplets causes arcing between the electrodes in the precipitator, resulting in a decrease in collection efficiency. Water condensation can be minimized by insulating the exhaust system ahead of the precipitator and the precipitator housing or by heating the airstream before it enters the precipitator. The heat added should be just sufficient to stop the arcing, because excessive heat vaporizes the oil and prevents its collection in the precipitator.

Electric insulators exposed to the contaminated airstream accumulate oil and water. These deposits result in electrical leakage with accompanying voltage drop and decrease in precipitator efficiency. Insulators should, therefore, be isolated from the contaminated airstream by being enclosed in channels. The channels should be pressurized slightly by small blowers to prevent infiltration of contaminant.

Maintenance of Precipitators

The oils collected in the precipitators venting asphalt saturators form tarry materials on the pre-

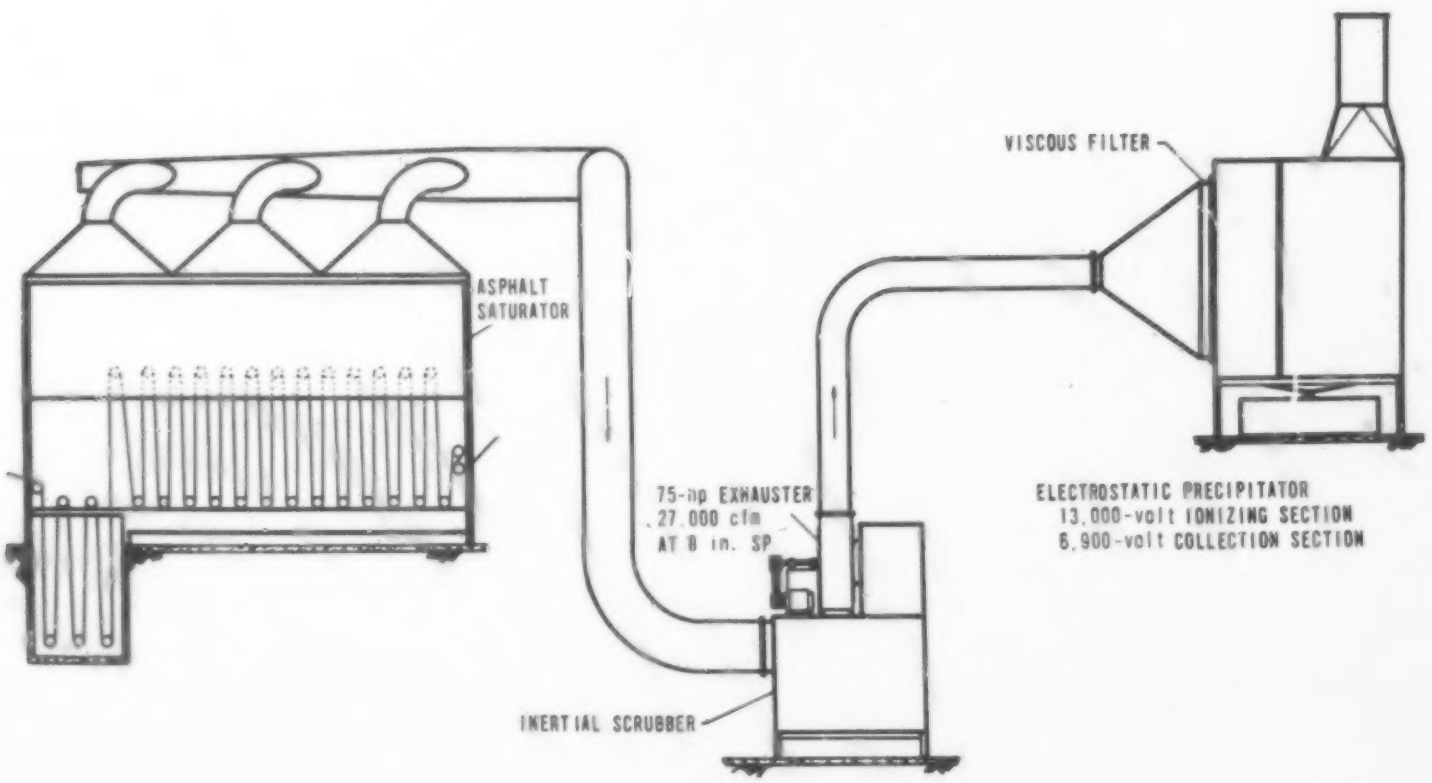


Figure 275. Schematic drawing of electrical precipitator, precleaner, and exhaust system for an asphalt saturator.

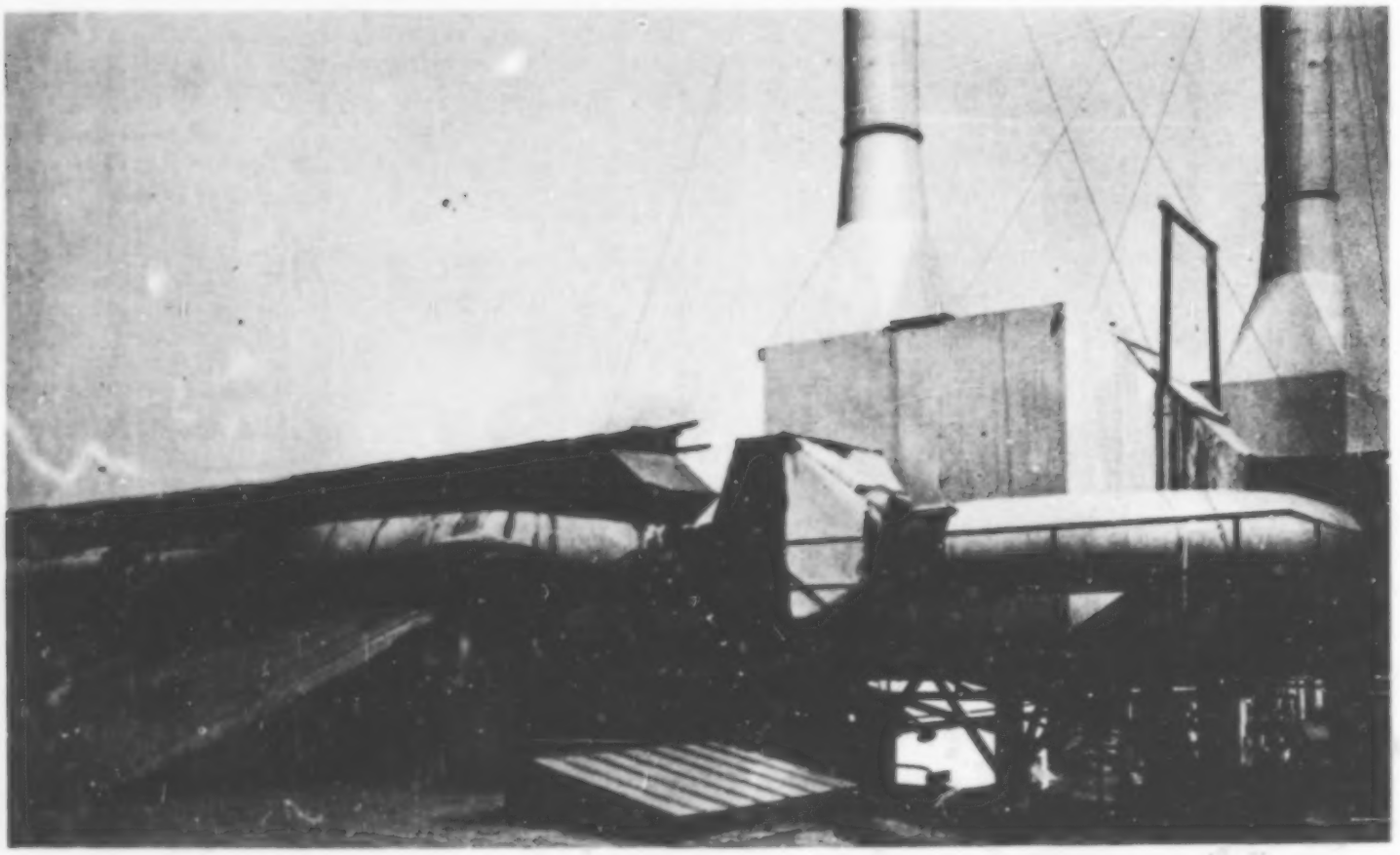


Figure 276. Low-voltage, two-stage electrical precipitator venting an asphalt saturator (Johns-Manville Products Corp., Los Angeles, Calif.).

cipitator's components. These deposits decrease the efficiency of the precipitator, causing insulating and arcing effects. Proper maintenance is vital if the precipitator is to eliminate the emissions from the saturator. Maintenance operations should include the following:

1. The interior components of the precipitator should be cleaned every 4 to 6 weeks by pressure spraying with water and detergent.

2. Regular checks should be made of the condition of all wires and insulators. Cracked or broken components should be replaced.

3. Components of the precipitator should be cleaned down to bare metal about twice a year.

These procedures should not be interpreted as rigid rules since individual installations vary considerably in regard to operating time and quantity of material collected.

Baghouses

Baghouse filters are occasionally used as air pollution control devices for asphalt saturators, but their use is limited as a result of maintenance problems associated with filter bag upkeep and their high power requirement. Oil collected by the filter fabric is oxidized and polymerized by the airstream, causing plugging of the fabric and increasing of the pressure drop across the filter unit. The air volume handled by the exhaust system then decreases because of increased pressure drop and results in loss of mist capture at the saturator's hood openings. Another problem associated with bag filters in this service is the reentrainment of collected oil in the airstream. A cyclone separator following the filter may be partially successful as an entrainment separator. Table 110 shows the results of a test on a bag filter unit followed by a cyclone separator.

Scrubbers

Spray-type scrubbers have met with limited success as air pollution control devices for saturators. Some spray scrubbers may have an efficiency, based on weight removed, as high as 90 percent, but the scrubber's effluent may be from 50 to 100 percent opaque, and may thus be in excess of that allowed by law. This opaque discharge is due to the extremely low collection efficiency of spray scrubbers for particles loss than 1 micron in diameter. These small-diameter particles, when

Table 110. EMISSIONS FROM A BAG FILTER AND CYCLONE SEPARATOR VENTING AN ASPHALT SATURATOR

	Control equipment inlet	Control equipment discharge
Volume, scfm	10,300	10,300
Temperature, °F	217	185
Emission rate,		
gr/scf	0.768	0.289
lb/hr	67.7	25.5
Water vapor, %	6.4	6.8
Collection efficiency, %		62.3

emitted from the scrubber discharge, cause maximum light scattering and, therefore, high opacities. Table 111 shows the results of tests made on a scrubbing system venting an asphalt saturator.

Theoretical evidence indicates that venturi-type scrubbers remove contaminants with particle sizes of less than 1 micron in diameter, but the high initial equipment cost and high energy requirements of the venturi scrubber make its use economically unattractive compared with other forms of air pollution control equipment.

Table 111. EMISSIONS FROM A WATER SCRUBBER VENTING AN ASPHALT SATURATOR

	Scrubber inlet	Scrubber discharge
Volume, scfm	12,000	12,196
Temperature, °F	138	92
Emission rate,		
gr/scf	0.535	0.0737
lb/hr	55.0	7.7
Water, %	2.7	4.2[a]
Collection efficiency, %		86

[a] At 3.7 volume % of water, vapor is saturated air. Other qualitative tests run simultaneously showed no particulate water.

SOLVENT DEGREASERS

INTRODUCTION

In many industries, metal-fabricated articles must be washed or degreased before their electroplating, painting, or other surface finishing. Most degreasing operations of any size are carried out in packaged units, termed degreasers, in which a chlorinated organic solvent, either in the gaseous or liquid state, is used to wash the parts free of grease and oil. Some measurable solvent is emitted as vapor from even the smallest degreaser, and the sheer number of these units in large manufacturing areas makes their combined solvent emissions significant to a community's air pollution.

Design and Operation

Designs of solvent degreasers run the gamut from simple, unheated wash basins to large, heated, conveyorized units in which articles are washed in hot solvent vapors. The vapor-spray unit depicted in Figure 277 is typical of the majority of industrial degreasers. Solvent is vaporized in the left portion of the tank either by electricity, steam, or gas heat. Solvent vapors rise and fill that portion of the tank below the water-cooled condensers. At the condensers there is a definite vapor line that can be observed from the top of the tank. Condensed solvent runs through the collection trough to the clean-solvent receptacle at the right of the tank. Articles to be degreased are lowered in baskets into the vapor space of the tank. Vapors condense on the metal parts, and hot condensate rinses oil and grease into the liquid receptacle. When necessary, the flexible hose and spray pump are used to rinse particularly dirty articles. Many degreasers are equipped with lip-mounted exhaust hoods that draw fumes from the top of the tank and vent them outside the working area.

Types of Solvent

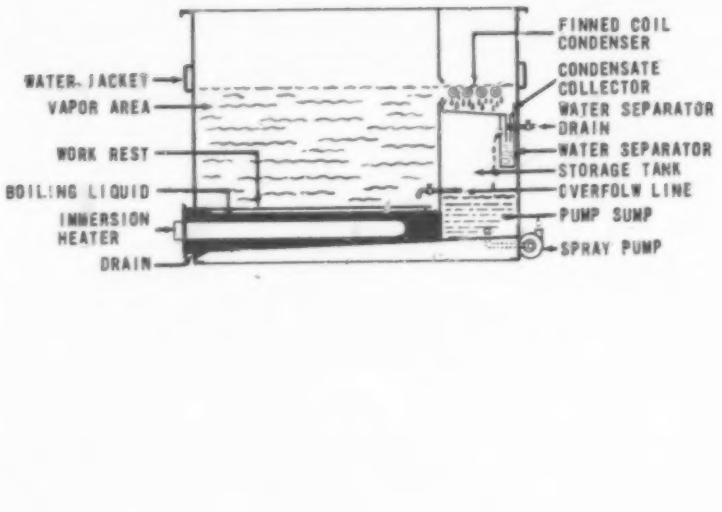
Nonflammable, chlorinated solvents are used almost exclusively with degreasers. An estimated 90 percent of the tonnage used for this purpose in Los Angeles County is trichloroethylene, $CHCl=CCl_2$, most of the remaining 10 percent being the higher boiling perchloroethylene, $CCl_2 = CCl_2$. Selection of solvent is usually dictated by operators' temperature requirements. Most greases and tars dissolve readily at the 189°F boiling point of trichloroethylene, and this is the apparent reason for its wide use. Perchloroethylene, which boils at 249°F, is consequently used only when higher temperatures or its slightly different chemical properties are required. Freon also finds occasional use in specialized degreaser applications.

THE AIR POLLUTION PROBLEM

The only air pollutant emitted from solvent-degreasing operations is the vapor of the organic solvent. Both trichloroethylene and perchloroethylene are considered slightly toxic. The American Conference of Governmental Hygienists recommends a maximum allowable concentration of 200 ppm for continuous 8-hour exposure to either solvent. Acute exposure produces dizziness, severe headaches, irritation of the mucous membranes, and intoxication. Chronic exposure can be fatal through damage to the liver and kidneys (Sax, 1963).

Solvent Losses

Daily emissions of solvent from individual degreasers vary from a few pounds to as high as



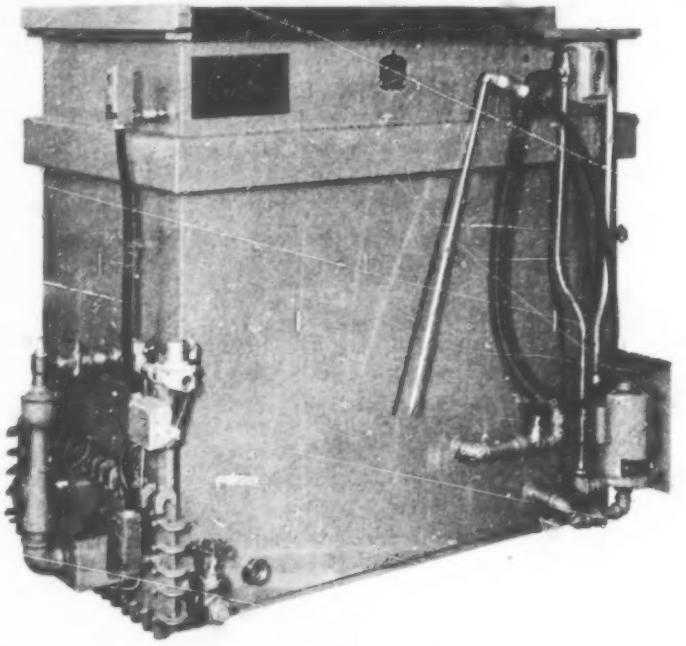


Figure 277. Vapor-spray degreaser (Catalog No. 10M359, Baron Industries, Los Angeles, Calif.).

1,300 pounds (two 55-gallon drums). Total emissions in large industrial areas are impressive. For example, in Los Angeles County degreasing operations are estimated to be responsible for the emission of 45 tons of chlorinated solvents per day. This represents some 70 percent of the halogenated solvent usage and about 7.5 percent of the total organic solvent usage in that area (Lunche et al., 1957).

Solvent is lost from degreaser tanks in essentially two ways: Vaporization (including diffusion) from the tank, and carryout with degreased articles. A leading degreaser manufacturer estimates that about 0.05 pound of solvent is lost by vaporization per hour per square foot of open tank area where there are no appreciable drafts across the top of the tank. Obviously, a much higher quantity of solvent is carried away when cross-drafts are strong.

The quantity of solvent carried out with the product (and later evaporated into the atmosphere) is a function of product shape and the method in which articles are distributed in the basket. In many instances, these losses can be greatly reduced by proper alignment in the degreaser's basket.

The cost of chlorinated solvents, currently about $2 per gallon, often makes installation of special equipment desirable to minimize vaporization and carryout losses and to recover solvent from the ventilator's exhaust gases.

HOODING AND VENTILATION REQUIREMENTS

Vapor spray degreasers are not usually ventilated. The condensing ring and the high density of the vapor are relied upon to retain the vapor in the tank. A small amount of vapor does escape, and general room ventilation is used to remove the vapor from the site. When a control device is used to collect the vapors from the tank, a lateral slot hood may be used, as shown in Figure 278. Slot hoods are also used sometimes without control devices. In both cases a minimum volume of air is used to prevent excessive loss of valuable solvent or to preclude overloading the control device. Slot hood velocities should not exceed 1,000 fpm for this service, and in many cases, by experimentation, these velocities may be reduced. Size of tank, objects degreased, and drafts within the building all influence slot velocities.

AIR POLLUTION CONTROL EQUIPMENT

Emission of solvent from degreasers can be minimized by location, operational methods, and tank covers. In a few cases, surface condensers and activated-carbon adsorbers have been used to collect solvent vapors.

Methods of Minimizing Solvent Emissions

In a discussion of degreaser operation, The Metal Finishing-Guidebook-Directory (1957) recom-

Figure 278. Vapor degreaser and hooding vented to activated-carbon unit shown in Figure 279 (General Controls, Burbank, Calif.).

mends several techniques for reducing losses of solvent and, consequently, air pollution:

1. A degreaser should always be located in a position where it will not be subject to drafts from open windows, doors, unit heaters, exhaust fans, and so forth. If possible, a 12- to 18-inch-high shield should be placed on the windward side of the unit to eliminate drafts.

2. Work items should be placed in the basket in such a way as to allow efficient drainage and prevent dragout of solvent.

3. Metal construction should be used for all baskets, hangers, separators, and so forth. Use of rope and fabric that absorbs solvent should be avoided.

4. The speed of work entering and leaving the vapor zone should be held to 12 fpm or less. The rapid movement of work in the vapor zone causes vapor to be lifted out of the machine.

5. Spraying above the vapor level should be avoided. The spray nozzle should be positioned in the vapor space where it will not create disturbances in the contents of the vapor.

6. Work should be held in the vapor until it reaches the vapor temperature where all condensation ceases. Removal before condensation has ceased causes the work to come out wet with liquid solvent.

7. When the metal articles are of such construction that liquid collects in pockets, the work should be suspended in the free-board area above the tank to allow further liquid drainage.

8. The degreaser tank should be kept covered whenever possible.

Tank Covers

As operators have become more cognizant of the costs of degreaser solvent and of the hazards to worker health, the use of intricate and sometimes costly tank closures has become popular. In earlier times, most degreasers were equipped with relatively heavy, metal, one-piece covers. The weight and unwieldy shape of these covers were such that few operators could be depended upon to place them over the tanks at the end of a working day. Since modern tank closures are operated hydraulically or electrically with foot levers, buttons, and so forth, workers can easily cover tanks, even during short periods of work stoppage. There are several varieties of automatically operated closures, one of which is shown in Figure 279. Most are fabricated of steel, screens, plastic, or plastic-impregnated fabric. Closure is usually by roll or guillotine action whereby vapor disturbance is minimal. The use of solid hinged lids should be avoided; however, hinged screen lids may be used.

The solvent saving and air pollution control that can be effected with automatic closures is a function of prior operating technique. Where degreaser operation has been relatively haphazard, the use of these covers has been shown to reduce emissions of solvent well over 50 percent. When a degreaser has been well located and operated, the savings provided by these devices has been small. Because of the high cost of chlorinated solvents, however, automatic closures frequently pay for themselves in short periods even at moderate usage of solvent.

Controlling Vaporized Solvent

While most solvent conservation efforts have been directed toward prevention of emissions at the tank, there are means by which these vapors can be removed from a carrying airstream that would otherwise be exhausted to the atmosphere. Practical control methods are extremely limited and, indeed, industrial application of chlorinated-solvent controls have, to date, been uncommon. Adsorption with activated carbon is, in fact, the only currently feasible means that can be adapted to most degreasers. Activated carbon has a relatively high

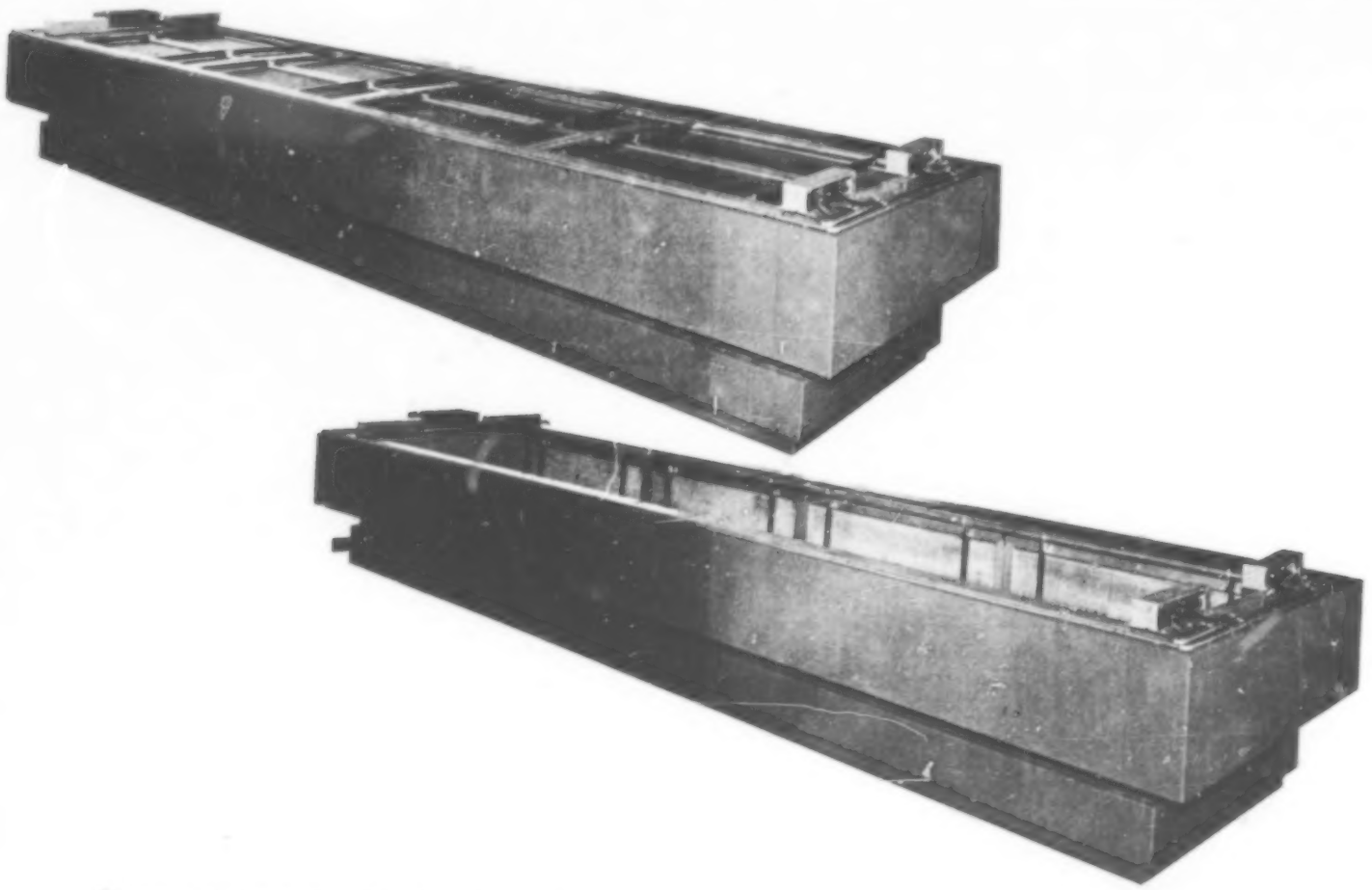


Figure 279. A hydraulically operated screen-type closure: (left) Cover in closed position, (right) cover in open position (Baron Industries, Los Angeles, Calif.).

capacity for both trichloroethylene and perchloroethylene, and adsorption units can be used to recover up to 98 percent of the solvent vapors in exhaust gases from a degreaser.

An activated-carbon adsorber used to recover trichloroethylene is shown in Figure 280. It consists essentially of two parallel-flow carbon chambers that can be operated either separately or simultaneously. Solvent-laden air is collected at spray degreasing booths, as depicted in Figure 281, and at the vapor degreaser, previously shown in Figure 278. The solvent-laden airstream is directed to both carbon chambers except when one chamber is being regenerated. A unit such as this must necessarily be designed to handle the required exhaust volume through only one chamber. The operator of this particular adsorber reports a 90 percent reduction in usage of chlorinated solvent (1,100 gallons per month) since its installation. Carbon adsorption is especially suitable for spray degreasing operations where the spray chamber must be exhausted to protect the operator.

When solvent concentrations in exhaust gases are relatively large, surface condensers can be used to collect appreciable quantities of solvent. The principal deterrent to the use of this type control

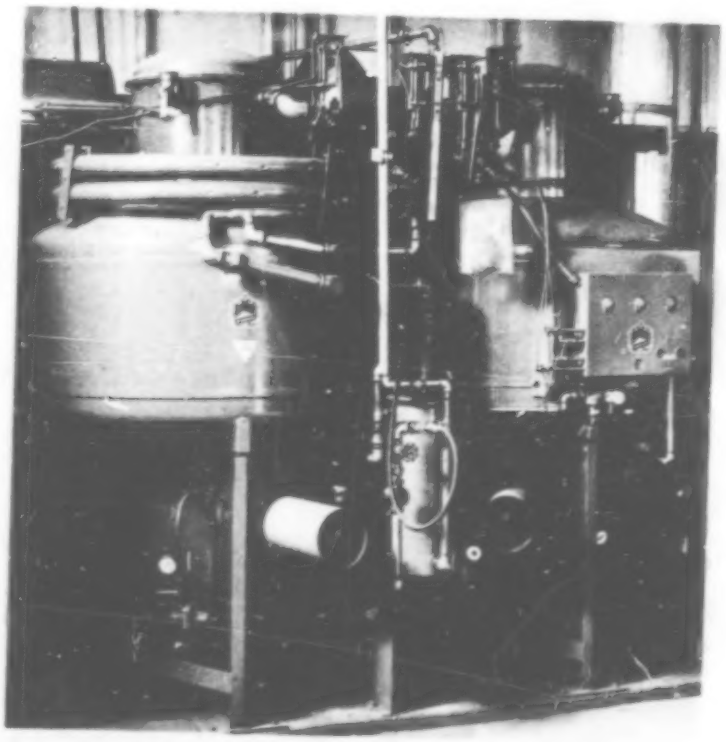


Figure 280. Two-chamber, activated-carbon adsorption unit used to recover trichloroethylene from degreasing exhaust gases (General Controls, Burbank, Calif.).

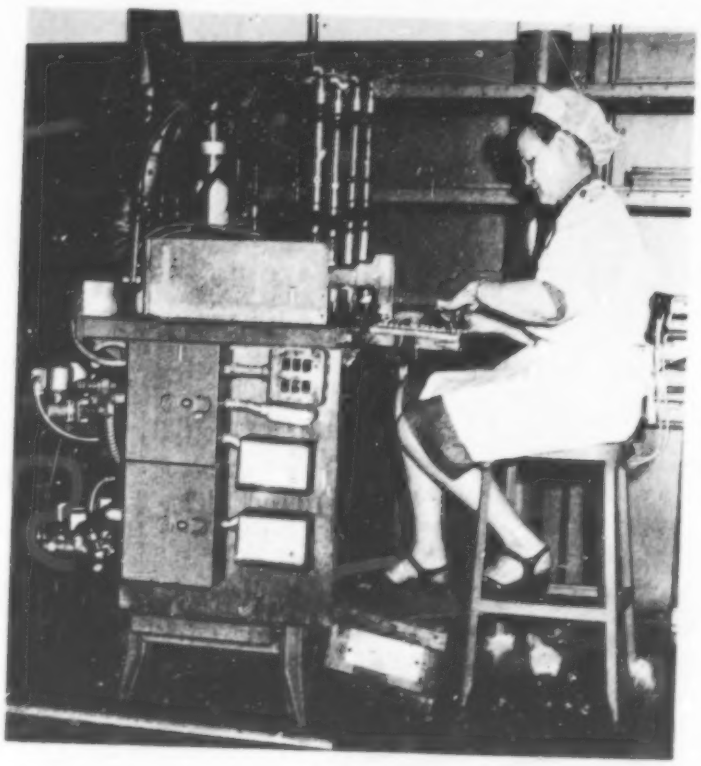


Figure 281. Spray degreasing table and hooding vented to activated-carbon unit shown in Figure 280 (General Controls, Burbank, Calif.).

is the small concentration of chlorinated solvent usually encountered in exhaust gases from degreasers. At the 68°F operating temperature of most atmospheric, water-cooled condensers, the trichloroethylene concentration can be held only to 7.4 percent, and the perchloroethylene concentration, to 2.4 percent. Chlorinated-solvent concentrations in exhaust gases from degreasers are usually well below these figures.

Since degreaser solvents are essentially noncombustible, incineration is not a feasible method of control. Moreover, the thermal decomposition of chlorinated solvents can produce corrosive and toxic compounds, such as hydrochloric acid and phosgene, which are more objectionable air contaminants than the solvents.

SURFACE-COATING OPERATIONS

INTRODUCTION

Many devices are used in the painting and coating of manufactured items. Basic coating operations include dipping, spraying, flowcoating, and roller coating. There are variations and combinations of these operations, each designed for a specific task. The coatings applied in these operations vary widely as to composition and physical properties. Table 112 gives some typical coating formulas.

Table 112. EXAMPLES OF SURFACE-COATING FORMULAS ON AN AS-PURCHASED BASIS

Type of surface coating	Composition of surface coating, %					
	Non-volatile portion	Hydrocarbons		Alcohols	Ketones	Esters and ethers
		Aliphatic	Aromatic			
Paint	44	56	-	-	-	-
Varnish	50	45	5	-	-	-
Enamel	58	10	30	2	-	-
Lacquer	23	7	30	9	22	9
Metal primer	34	33	33	-	-	-
Glaze	80	-	20	-	-	-
Resin[a]	50	-	-	-	-	-
Sealer	50	40	-	-	-	10
Shellac	50	-	-	50	-	-
Stain	20	-	80	-	-	-
Zinc chromate	60	-	40	-	-	-

[a]Contains 50% solvent of an unspecified type.

Spray Booths

In spraying operations, a spray gun, usually operated by compressed air, is used to spray the paint on the object to be painted. A booth or enclosure, ventilated by a fan, provides a means of ventilating the spray area to protect the health of the spray gun operator and ensure that an explosive concentration of solvent vapor does not develop. Table 113 shows threshold limit values of typical paint solvents. These values are average concentrations to which workers may be safely exposed for an 8-hour day without adverse effect on their health. The spray booth may also be equipped to filter incoming air as well as remove particulate matter from the exhausted air. A typical paint spray booth is shown in Figure 282.

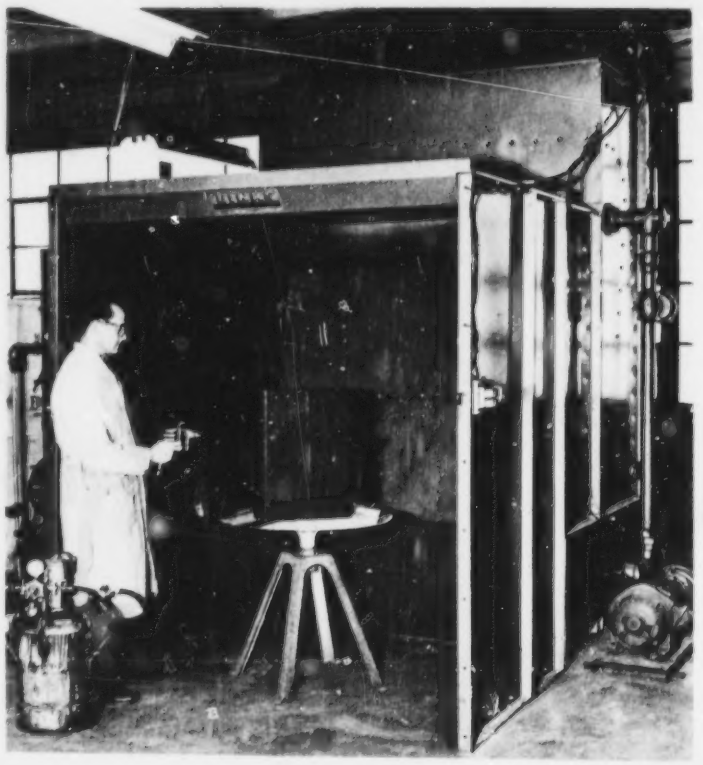


Figure 282. A typical water wash-type spray booth (Binks Manufacturing Company, Los Angeles, Calif.).

Table 113. THRESHOLD LIMIT VALUES OF TYPICAL PAINT SOLVENTS

	Lower explosive limit (LEL) [a]		25% of LEL, ppm	Maximum allowable concentration, [b] ppm
	%	ppm		
Acetone	2.15	22,000	5,500	1,000
Amyl acetate	1.1	11,100	2,770	200
Methyl ethyl ketone	1.81	18,400	4,600	250
Butyl acetate	1.7	17,300	4,320	200
Cellosolve	2.6	26,700	6,670	200
Cellosolve acetate	1.71	17,400	4,350	100
Ethyl acetate	2.18	22,300	5,570	400
Ethanol	3.28	33,900	8,470	1,000
Naphtha (petroleum)	0.92 to 1.1	9,290	2,320	500
Toluene	1.27	12,600	3,150	200
Xylene	1.0	10,100	2,520	200
Mineral spirits	0.77	7,760	1,940	500

[a] Adapted from: Factory Mutual Engineering Division, Handbook of Industrial Loss Prevention, McGraw-Hill Book Co., Inc., New York, 1959.

[b] Adapted from: American Medical Association Archives of Environmental Health, 14:186-89, 1956.

Flowcoating Machines

Flowcoating consists of flowing the paints in a steady stream over the work suspended from a conveyor line. Excess paint drains from the work to a basin from where it is recirculated by a pump back to the paint nozzles. Figures 283 and 284 show typical flowcoating machines.

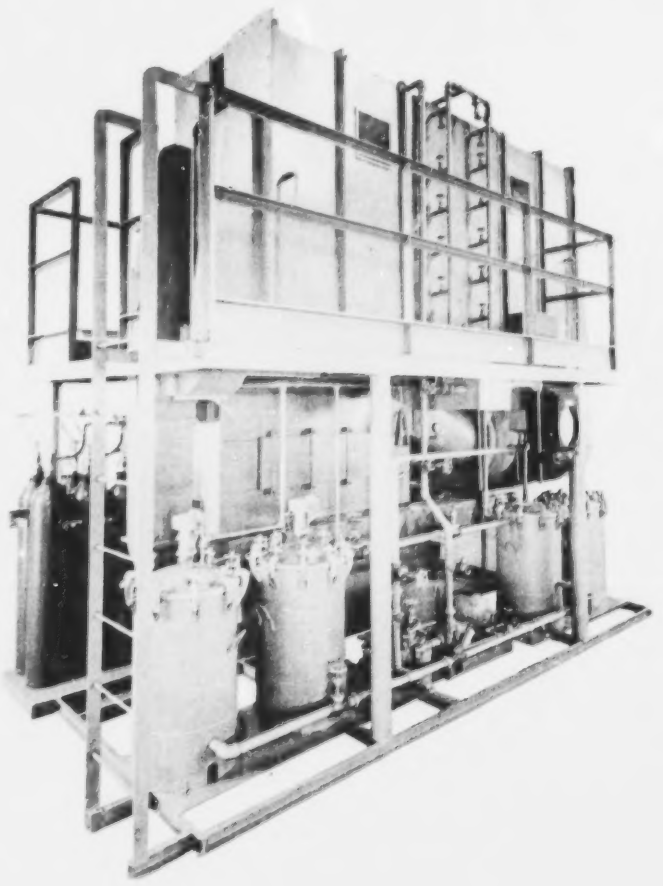


Figure 283. Side view of a flowcoating machine (Industrial Systems, Inc., Southgate, Calif.).

Paint Dip Tanks

Paint dip tanks are simple paint containers, frequently with conical bottoms. The object to be coated with paint is immersed and then removed. Provision is made to drain the excess paint from the work back to the tank, either by suspending the work over the container or by using drainboards that drain back to the dip tank. Some method is usually provided for agitation of the paint in the tank, in order to keep a uniform mixture. The most frequently used method consists of pumping paint from the tank bottom to a point near the tank top but still under the liquid surface.

Figure 284. View of a flowcoating machine showing drain decks and enclosures (Industrial Systems, Inc., Southgate, Calif.).

Roller Coating Machines

Paint roller coating machines are similar to printing presses in construction. The machines usually have three or more power-driven rolls. One roll runs partially immersed in the paint. This roll transfers the paint to a second roll parallel to it. The sheet work to be coated is run between the second and a third roll and is coated by transfer of paint from the second roll. The quantity of paint applied is established by the distance between the rolls through which the sheet passes.

THE AIR POLLUTION PROBLEM

Air Contaminants From Paint Spray Booths

The discharge from a paint spray booth consists of particulate matter and organic-solvent vapors. The particulate matter consists of fine paint particles, whose concentration seldom exceeds 0.01 grain per scf of unfiltered exhaust. Despite this small concentration, the location of the exhaust stack must be carefully selected so as to prevent paint spotting on neighboring property.

The solvent concentration in the spray booth effluent varies from 100 to 200 ppm. The solvent emission out the spray booth stack varies widely with extent of operation, from less than 1 pound per day to over 3,000 pounds per day. Paint solvent vapors evidently take part in the photochemical smog reactions leading to products that result in eye irritation. Their odors may also cause local nuisances. Essentially all the solvent in the coating mixture is eventually evaporated and emitted to the atmosphere.

Air Contaminants From Other Devices

Air contaminants from paint dipping, flowcoating, and roller coating exist only in the form of organic-solvent vapors since no particulate matter is formed.

HOODING AND VENTILATION REQUIREMENTS

Requirements for Paint Spray Booths

The usual spray booth ventilation rate is 100 to 150 fpm per square foot of booth opening. Insurance standards require that the enclosure for spraying operations be designed and maintained so that the average velocity over the face of the booth, during spraying operations, is not less than 100 fpm.

Requirements for Other Devices

Dip tanks, flowcoaters, and roller coaters are frequently operated without ventilation hoods. When local ventilation at the unit is desirable, a canopy hood may be installed.

AIR POLLUTION CONTROL EQUIPMENT

Control of Paint Spray Booth Particulates

A considerable quantity of particulate matter results from the use of the common air atomization-type spray gun. During painting of flat panels, a minimum of 35 percent of the paint sprayed is not deposited on the panels and is called overspray. During the spraying of other articles, the overspray may be as high as 90 percent; however, 60 percent overspray is more common. Particulate matter in paint spray booths is controlled by baffle plates, filter pads, or water spray curtains. Baffle plates control particulates from enamel spraying by adhesion, with removal efficiencies of 50 to 90 percent. Baffle plates have very low efficiencies in collecting lacquer spray particulates because of the rapid drying of the lacquer and consequent slight adhesion to the baffles.

Filter pads satisfactorily remove enamel and lacquer particulates with efficiencies as high as 90 percent. The filtering velocity should be less than 250 fpm.

Water curtains and sprays are satisfactory for removing paint particulates, with efficiencies up to

95 percent. A water circulation rate of 10 to 38 gallons per 1,000 cubic feet of exhaust air is customary. Surface-active agents are added to the water to aid in the removal of paint from the circulating tank.

Control of Organic Vapors From Surface Coatings

Known solvent recovery processes make use of condensation, compression, absorption, distillation, or adsorption principles. Organic solvents used in coatings are not controllable by filters, baffles, or water curtains. In view of the small solvent vapor concentration in the airstream from the spray booth or applicator hood, the only economically feasible solvent control method is adsorption. Recent work (Elliott et al., 1961) indicates that adsorption by activated carbon can be a feasible method for the control of paint solvents. This work indicates that control efficiencies of 90 percent or greater are possible, provided particulates are removed from the contaminated airstream by filtration before the airstream enters the carbon bed. General design features of adsorption-type devices have been discussed in Chapter 5.

PIPE-COATING EQUIPMENT

INTRODUCTION

Iron and steel pipes are subject to corrosion and oxidation, particularly in underground service. In order to exclude the corrosive elements from contact with the metal, many surface coatings have been used. These include paints, lacquers, metallic coatings, vitreous enamels, greases, cements, and bituminous materials, both asphalt and coal tar based. Only the bituminous materials will be discussed in this section.

Asphalt, a residue derived from the distillation of crude petroleum, becomes a dark brown to black rubbery solid when air blown at elevated temperatures and allowed to cool. Coal tar is a dark brown to black, amorphous, solid residue resulting from the destructive distillation of coal. Both materials are compounded with mineral fillers and other ingredients to form the so-called enamel that is applied to the pipe. Both materials perform essentially the same duty with some qualifications. Without the addition of plasticizers, the coal tar enamels tend to have a fairly narrow satisfactorily operating temperature range. Above or below this range, they are too soft to stay in place or too brittle to resist impact. The asphalts have a wider operating temperature range but have a disadvantage of being slightly more permeable to moisture and are affected more by soil minerals. Some common qualities that make these materials excellent for pipe coatings are as follows:

1. They resist moisture, and chemical and electrolytic action.
2. Long-lasting adhesion can be expected between the coating and pipe.
3. They are stable over a wide temperature range if properly compounded.
4. They are tough and resist mechanical abrasion.
5. They possess good ductility and can resist soil contraction and expansion and underground pipe movement
6. They resist aging over long periods of time.

METHODS OF APPLICATION

The three usual methods of applying asphalt or coal tar coatings to pipe are dipping, wrapping, and spinning (The Asphalt Institute, 1954; American Water Works Association, 1951). These will be discussed individually. With all application techniques the pipe must be dry and rust free. Most often a primer is applied before the final coating is added.

Pipe Dipping

Pipe dipping involves applying the coating to both the internal and external surfaces of the pipe by completely immersing it in a large vat of molten asphalt. Coal tar enamel cannot be applied by dipping since it cannot be held in an open container for long periods of time without excessive changes in its physical properties. The tank used is usually rectangular with dimensions to accommodate the largest size pipe to be dipped. The asphalt is kept at a specified temperature by heat-transfer tubes submerged in the enamel. The pipe is lowered into the enamel until completely covered and allowed to remain until the metal reaches the temperature of the liquid. This is necessary for good adhesion. It is then raised, tilted off horizontal in order to drain off excess enamel, and allowed to cool. Additional thickness may be obtained by redipping. For the second and succeeding dips, however, the pipe must not remain in the tank long enough to remelt the material already deposited.

Pipe Spinning

Pipe spinning is the name given to the procedure wherein molten asphalt or coal tar enamel is applied to the interior surface of a rotating pipe. The spinning motion is given to the pipe by conveyor

wheels or endless chain slings. The enamel is applied by spray heads on a lance attached to a traveling, heated, enamel kettle. The lance is inserted the full length of the pipe and then the hot enamel is sprayed as the lance is withdrawn. The spinning of the pipe deposits the enamel in a uniform layer and holds it in place until it hardens. The spinning is continued with usually a cooling water spray on the outside of the pipe until the enamel temperature has cooled to about 100°F.

Pipe Wrapping

Pipe wrapping is the most complex of the common pipe protection techniques involving asphalt and coal tar because, in addition to the enamel, wrappings of rag or asbestos felt, plastic film, fiberglas, metallic foil, kraft paper, or a combination of these are used. Two types of equipment are used. One type consists of apparatus both to rotate the pipe and move it longitudinally past a stationary enamel dispensing and wrapping station, as shown in Figure 285. In the other method, only the pipe rotates, and the coal tar or asphalt kettle and wrapping equipment travel on a track along the length of the pipe (Figure 286).

The purpose of the wrapping is to make the pipe covering more durable during handling and installing as well as increase its aging and moisture exclusion properties. The enamel has a dual purpose--in addition to its corrosion-resisting function, it serves as an adhesive for the wrapping.

Preparation of enamel

Both coal tar and asphalt are shipped to the consumer in solid, 100-pound, cylindrical or octagonal castings or in 55-gallon fiber drums weighing about 650 pounds. Before being charged to the melting equipment the material is manually chopped into chunks weighing 20 pounds or less. The material is melted and kept at application temperature in natural gas-, oil-, or LPG-fired kettles.

THE AIR POLLUTION PROBLEM

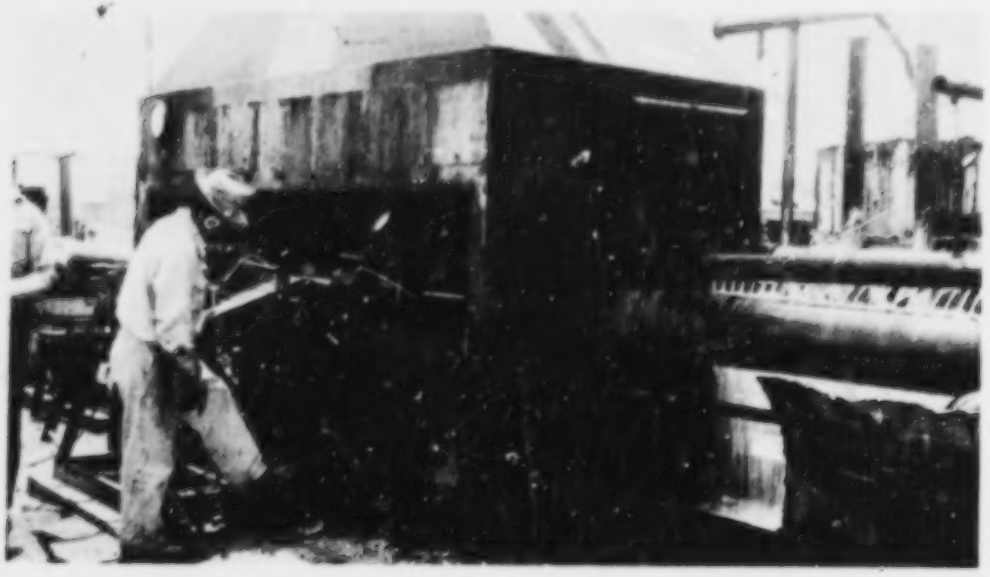
By far the largest source of air pollution from asphalt or coal tar operations is the dense white emissions caused by vaporization and subsequant condensation of volatile components in the enamel. This cloud is composed of minute oil droplets and is especially dense whenever the surface of the molten enamel is agitated. These emissions are objectionable on three counts that include opacity, odor, and toxicity--those from coal tar being the more objectionable. The visible emissions are intense enough to violate most opacity regulations. The odor of the emission is pungent and irritating with considerable nuisance-creating potential, and there may be the added nuisance caused by settling oil droplets. Lastly, the condensed vapors and gases are toxic. Prolonged breathing or skin exposure can cause itching, acne, eczema, psoriasis, loss of appetite, nausea, diarrhea, headache, and other ailments. Some medical researchers have stated that the fumes may also have some cancer-producing potential, but this has not been completely substantiated.

Although the fumes are dense, the actual weight of material emitted is relatively small. Tests conducted on pipe-wrapping operations using both asphalt and coal tar enamels have shown emissions ranging from a low of 1.8 pounds per hour to a maximum of 17.5 pounds per hour.

HOODING AND VENTILATION REQUIREMENTS

Because of the nature of all three of the methods used to apply asphalt and coal tar enamels to pipe, collection of the contaminants is difficult. Large quantities of air are entrained because hoods usually cannot be placed close to the point of emission. In the pipe-dipping operation, after being immersed, the pipe must be raised vertically above the tank and allowed to drain. Although lip-type hoods around the tank periphery may collect most of the tank emissions, those from the pipe itself cannot be collected by these hoods. In wrapping, especially for the traveling application type of equipment, a hood as long as the pipe itself would be necessary. A relatively small hood over the wrapping and tar-dispensing equipment can be used in the stationary kettle type of wrapper. In the spinning operation, emissions come from both ends of the pipe. Because of the need for working with various pipe lengths, hoods at both pipe ends are not practical. One solution is to install a stationary hood at the end of the pipe where the lance is inserted. A portable fan or blower is used at the other end to blow air through the pipe, conveying the emissions to the hood at the other end.

Another solution of the fume collection problem is to house all the equipment and vent the building to the air pollution control system selected. The building itself then becomes the collection hood. This, of course, dictates a large exhaust air volume to provide enough draft to prevent fume accumulation and maintain adequate room ventilation for the workers' comfort and safety. This method may not be necessary for an isolated spinner or wrapper, but for a dipping process or a process using several coating operations, it is more satisfactory than using local exhaust systems. As adjuncts to the overall building exhaust system, some local hoods at points of heavy emissions may be desirable, especially if these points are in areas frequented by operating personnel.



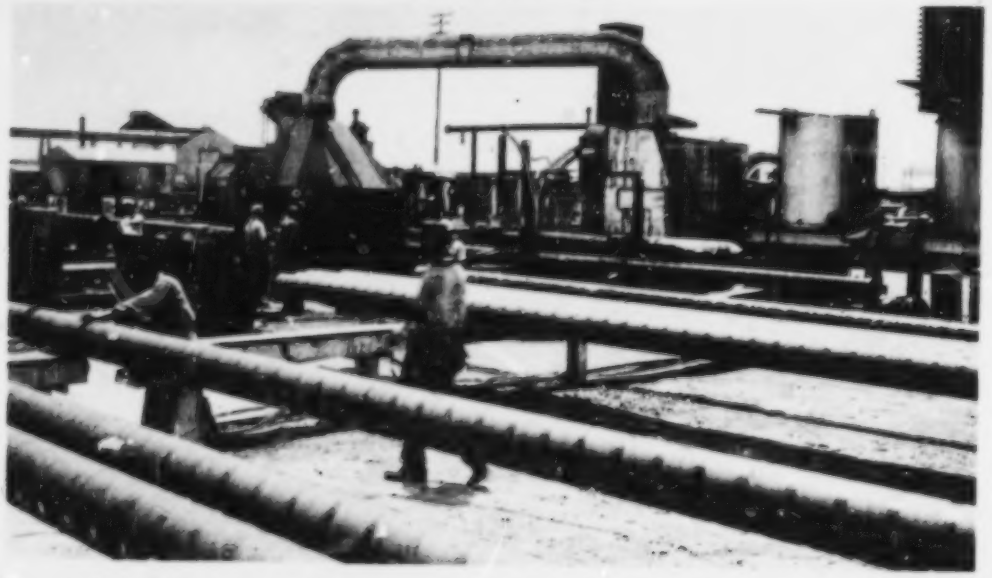


Figure 285. Stationary kettle type of pipe-wrapping equipment and scrubber: (top) Closeup, (bottom) overall view (Pacific Pipeline Construction Co., Montebello, Calif.).

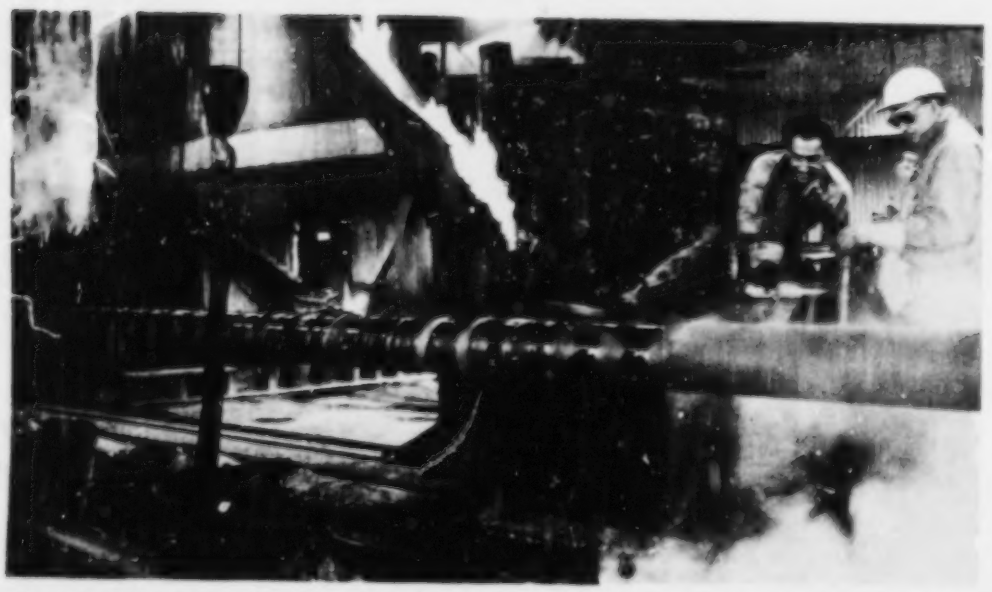


Figure 286. Traveling kettle-type pipe-wrapping equipment (Southern Pipe and Casing Co., Azusa, Calif.).

AIR POLLUTION CONTROL EQUIPMENT

Three basic types of devices can be considered for control of the emissions from asphalt and coal tar application. These are (1) scrubbers, (2) incinerators (afterburners), and (3) electrical precipitators.

Water scrubbers have been used most frequently for controlling pipe-coating equipment opacity, droplets, and odors. The baffled, water spray type of scrubber has been employed almost exclusively. These scrubbers have been operating satisfactorily by employing 30 gpm water per 1,000 cfm air to be scrubbed, at a water pressure of 50 psig. A typical scrubber system of this type is shown in Figure 287.

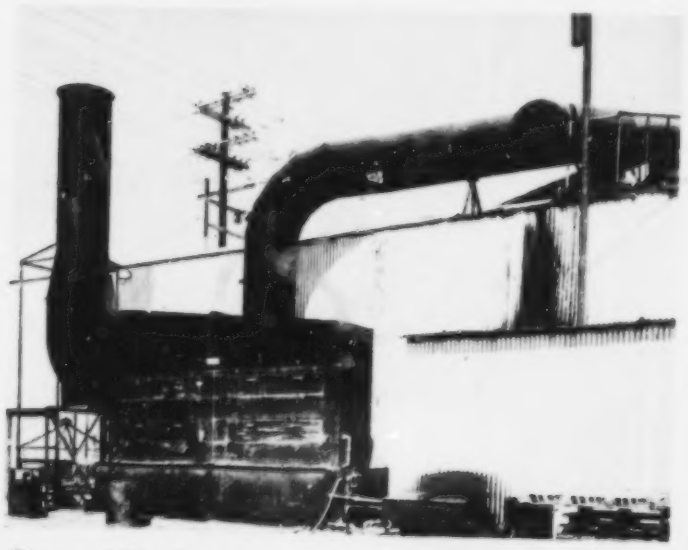


Figure 287. Scrubber system to control emissions from a pipe-wrapping and pipe-spinning operation (Southern Pipe and Casing Co., Azusa, Calif.).

The efficiency of scrubbers can be affected not only by their basic design, but by operational variables. Of most importance, the scrubber water must be kept clean. If scum and oil are allowed to collect for any extended period, and the dirty water is recirculated, the spray heads begin to plug, and this lowers the water rate and reduces the efficiency. An automatic skimming device is helpful, but, even so, frequent water changes are needed. In some instances, daily water changes and thorough weekly cleaning, including spray heads, have been necessary.

Properly designed and operated water scrubbers serving pipe-dipping, pipe-wrapping, and pipe-spinning operations have been shown by tests to have collection efficiencies of about 80 percent on a weight basis and to reduce visible emissions from 70 percent opacity to 10 to 15 percent opacity.

Incineration is the most positive method of complete control, but economic factors practically eliminate its application. This is due to the large quantity of air with a relatively small concentration of contaminants that must be heated to incineration temperatures of 1,200° to 1,400°F. For example, a typical building housing pipe-wrapping and pipe-spinning operations might require an exhaust volume as great as 40,000 cfm for adequate contaminant removal. Heating of this air from 80° to 1,200°F would require about 50 million Btu per hour. Thus, the operating cost as well as the initial cost of the relatively large unit required makes an afterburner unfeasible.

Electrical precipitators can be used for controlling emissions from pipe-coating operations, but, again, their high initial cost, as compared with that of scrubber systems, has made them unattractive. When, however, some of the maintenance and cleaning problems connected with scrubbers, as well as the higher basic scrubber-operating costs are considered, the higher installation cost for precipitators may be counterbalanced. Precipitators have been used successfully for controlling the emissions from roofing and building paper saturators. In this operation the emissions are of the same type as those from pipe coating, but are generally much greater in concentration and quantity. In practically all cases a precleaner, such as a wet dynamic precipitator, is used to remove large particles and prevent excessive tar buildup on the precipitator parts. For pipe-coating operations, the lower overall emissions may obviate the need for the precleaner.

Although scrubbers have proved to be satisfactory control devices for pipe-coating equipment, their effectiveness cannot be described as excellent. More research is needed on this air pollution control problem to achieve higher collection efficiencies and complete elimination of odors and visible emissions.

DRY CLEANING EQUIPMENT

Dry cleaning is a process of cleaning soiled textiles, usually clothes, with organic solvents. The textiles are cleaned by agitation in a solvent bath and by rinsing with clean solvent. Excess solvent is thrown off by centrifugal action in a rotating extractor, and the textiles are then tumbled to a dry state in warm air. The solvent is reclaimed for reuse by filtration and distillation. The filter cake may be cooked as a further solvent recovery measure. Figures 288, 289, and 290 illustrate the various cleaning equipment.

Dry cleaning equipment follows two basic designs. One design is tailored for petroleum solvents, and the other, for chlorinated hydrocarbon, or synthetic,

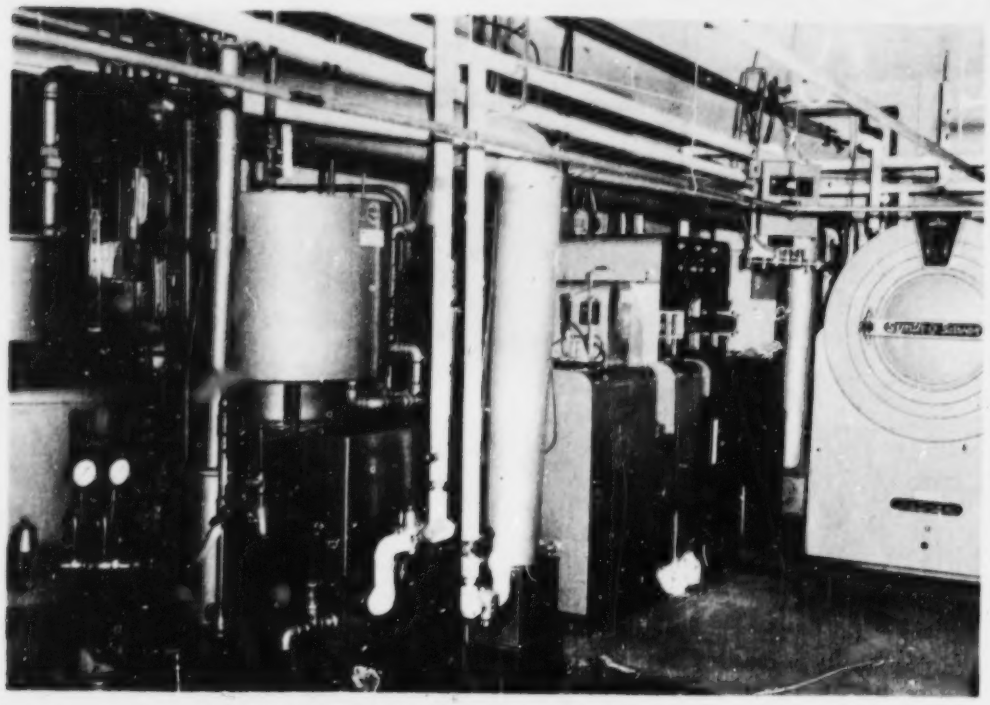


Figure 288. Synthetic-solvent dry cleaning unit with an activated-carbon adsorber (Joseph's Cleaners and Dyers, Los Angeles, Calif.).

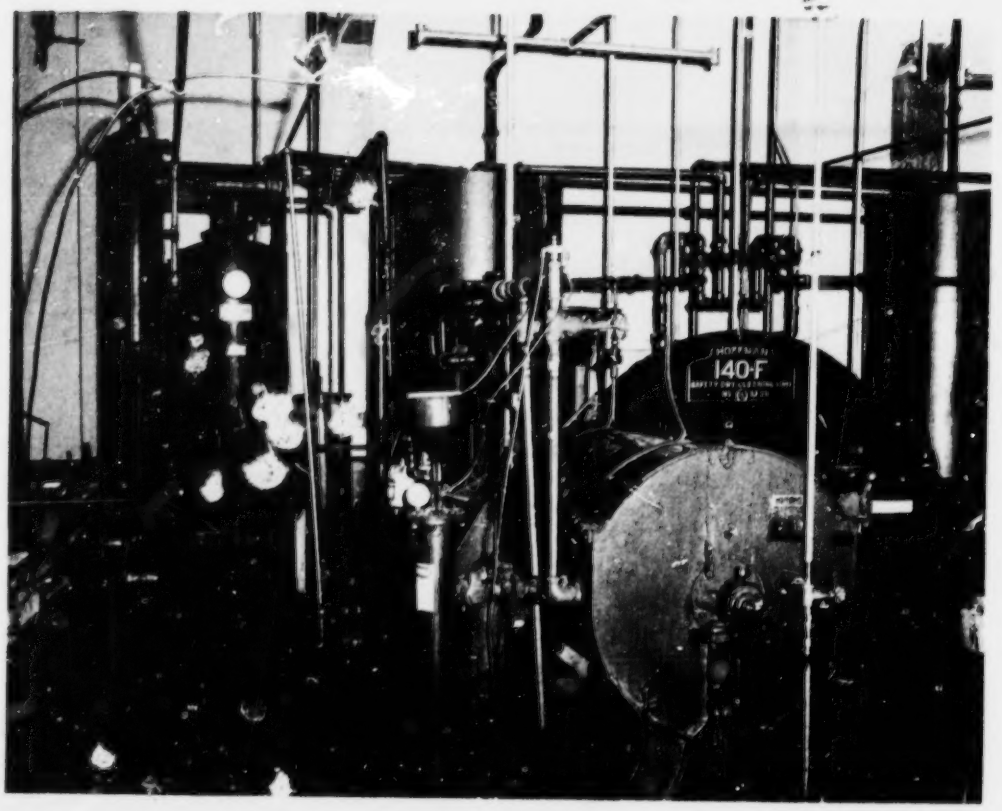


Figure 289. Petroleum solvent dry cleaning unit (Century Park Cleaners, Inglewood, Calif.).

Figure 250. Synthetic-solvent, coin-operated dry cleaning unit (Norge Sales Corp., Los Angeles, Calif.).

solvents. The increasingly popular coin-operated machine, a totally enclosed and smaller automatic version of a synthetic-solvent unit, incorporates the features of the larger synthetic-solvent units.

In a petroleum solvent dry cleaning plant, the equipment generally includes a washer, centrifuge, tumbler, filter, and, in many instances, a batch still. The washer consists of a perforated, horizontal, rotating drum enclosed in a vaportight housing. Housing and drum are each equipped with a closure for loading and unloading. A tank in the bottom of the housing serves as a reservoir for solvent. The centrifuge, called an extractor, is used to spin off solvent adhering to the clothes. Solvent drains through perforations in the centrifuge basket and is piped to a tumbler, similar to the washer but equipped with a blower and heater, and used to circulate hot air through the clothes and exhaust it to the atmosphere. Auxiliary equipment consists of a filter to remove suspended material from the solvent and a batch still to purify the solvent for reuse.

With perchloroethylene, the washer and extractor are combined in a single unit. The tumbler is equipped with a condenser for recovery of solvent vapor. The tumbler is a closed system while in operation and is vented to the atmosphere only during a short deodorizing period. A muck cooker is often used to reclaim solvent from filter sludge.

THE AIR POLLUTION PROBLEM

Solvents

As previously mentioned, two types of solvents are commonly used by the dry cleaning industry. These are the petroleum solvents, of which Stoddard solvent and 140°F solvent are most representative, and chlorinated solvents, hydrocarbon or synthetic, of which perchloroethylene, also known as tetrachloroethylene, is most representative. Small quantities of proprietary compounds may be added to the solvent by the dry cleaning operator to aid in the cleaning action of the solvent and to yield other beneficial effects. Table 114 lists some properties of these solvents.

Table 114. PROPERTIES OF DRY CLEANING SOLVENTS (Mellan, 1944, 1957)

Property	140°F	Stoddard	Perchloroethylene
Distillation range, °F	358 to 396	305 to 350	250 to 254
API gravity	47.9	50.1	-
Specific gravity at 60°F	0.789	0.779	1.61
Lb/gal	6.57	6.49	13.4
Paraffins, %	45.7	46.5	-
Naphthenes, %	42.2	41.9	-
Aromatics, %	12.1	11.6	-
Flash point (TCC), °F	140	100	Extinguishes fire
Corrosiveness	None	None	Slight on metal
Caution	Flammable	Flammable	Toxic
Odor	Mild	Sweet	Similar to ether's
Color	Water white	Water white	Colorless
Cost, $/gal	0.21	0.20	1.00

The dry cleaning industry contributes to air pollution by the release of organic-solvent vapors to the atmosphere. A good dry cleaning solvent is necessarily volatile, and this volatility can result in emissions of solvent when storage tanks are loaded, equipment doors are opened, ductwork or equipment leaks, and textiles dripping solvent are removed from equipment. The amount of solvent emitted to the atmosphere from any one dry cleaning plant is dependent upon the equipment used, the length of certain operations in the cleaning process, the precautions used by the operating personnel, and the quantity of clothes cleaned. The most important of these items are the precautions used and the weight of clothes cleaned.

A typical synthetic-solvent plant processes 2,000 pounds of textiles per 5-day week and can clean from 3,000 to 14,000 pounds, with an average of 5,500 pounds of textiles per 55-gallon drum of solvent (a consumption of 10 gallons of solvent for each 1,000 pounds of textiles). This average includes solvent recovered from filter sludge or muck.

The low cost of petroleum solvent provides little economic incentive to the operator of a petroleum solvent dry cleaning plant to conserve solvent and prevent or control its emission to the atmosphere. Emission of solvent vapors occurs primarily from the vent on the tumbler, and to a lesser extent, during the transfer of wet textiles from one piece of equipment to another and during disposal of filter sludge. These emissions are increased by poor operational practices. An average petroleum solvent plant may process about 6,000 pounds of textiles per 5-day week and usually cleans about 65 pounds of textiles per gallon of solvent (a consumption of 15 gallons of solvent for each 1,000 pounds of textiles).

Obviously then, the use of petroleum solvents results in the emission to the atmosphere of, on an average, 50 percent more solvent (by volume) than is emitted with the use of chlorinated solvent. Because a gallon of chlorinated solvent is much heavier than a gallon of petroleum solvent, its use results in a 40 percent greater emission (by weight) of perchloroethylene.

Lint

The lint generated when fabrics are tumbled dry must be removed before the air is discharged to the atmosphere. This is a minor problem, easily solved by devices not normally considered to be air pollution control equipment. The synthetic-solvent tumblers are provided with a cloth bag to filter the lint from the exhaust air. It is usually cleaned out at the completion of the daily operation. The petroleum solvent tumblers are generally exhausted to a separate lint trap that is filled with water and operates on the wet-impingement principle. These lint traps must be cleaned regularly to prevent the discharge of lint, which can sometimes cause nuisance complaints, or the accumulation of lint, which restricts airflow and increases the hazards of fire and explosion.

HOODING AND VENTILATION REQUIREMENTS

Because of safety requirements, hooding and ducting are an integral part of all dry cleaning equipment. In synthetic-solvent plants, vents are provided near the doors of the washer-extractor and the tumbler. An exhaust system is automatically activated whenever these doors are opened, and the system exhausts the vapors resulting from transfer of the wet textiles. When a carbon adsorption unit is used to collect the perchloroethylene vapors, floor vents are also provided to capture vapors from other areas.

Ventilation requirements must meet the regulations as delineated by the rules governing fire hazards and toxicity. For Stoddard and 140°F solvent, the concentration of vapor in and about the equipment must not exceed 500 ppm by volume in the air, to meet health requirements. This is considerably less than the quantity permissible to prevent a fire hazard.

Perchloroethylene is not flammable but is toxic and the allowable concentration must not exceed 200 ppm by volume in air, which represents the maximum amount to which a person may be exposed for 8 hours a day over a long period without endangerment to health.

AIR POLLUTION CONTROL EQUIPMENT

The application of activated-carbon adsorption to control solvent vapor emissions from dry cleaning equipment in which perchloroethylene is used is dictated by economics. With other factors equal, the tenfold difference in cost per gallon between chlorinated and petroleum solvents forces the user of chlorinated solvents to obtain the maximum number of pounds of textiles cleaned per gallon of solvent used in order to compete in terms of price. This means reducing solvent consumption to a minimum by efficient operation.

Packaged adsorption units using activated carbon are available to the operator of a synthetic-solvent cleaning plant for recovering perchloroethylene vapor that would normally be discharged to the atmosphere. The adsorption unit is added to the discharge of the ventilating system. Vapor laden air collected from the washer-extractor, tumbler, and floor vents passes through a filter for removal of entrained solids and then to the adsorber. Collection of the solvent is 100 percent up to the breakpoint of the carbon at the particular vapor concentration and temperature. Good operation dictates that the adsorption cycle stop short of this point. Recovery of the solvent is effected by passing low-pressure steam through the carbon. The steam-vapor mixture is cooled and condensed, and the solvent is separated from the water by decantation and returned to the solvent storage tank for reuse. The value of the solvent recovered makes possible the amortization of the adsorption unit within 1 to 2 years.

Activated-carbon adsorption can also be adapted to control the solvent emissions from the petroleum solvent dry cleaning plant, but the lower value of the recovered solvent requires a much longer period of time to pay the cost of the equipment.

Other methods of reducing emissions from dry cleaning plants include good operational procedures and equipment maintenance. In the petroleum solvent plant, because of the low cost of the solvent, minor leaks are likely to go unnoticed or unattended in favor of uninterrupted production.

Operational procedures that affect solvent emissions include the transfer of solvent-wet textiles from washer to extractor to tumbler. Where the washer and extractor are combined, a considerable saving in solvent is obtained, but the capacity of the washer is reduced. This operation is usually separated in petroleum solvent cleaning but combined in the synthetic-solvent plant. Since the solvent remaining in the fabric after extraction can be discharged to the atmosphere by evaporation during the tumbling and deodorizing operation, the time period allowed controls the quantity of solvent discharged.

In synthetic-solvent cleaning plants, tumblers are equipped with a heater and fan to circulate warm air through the clothes and are operated as a closed system during the drying cycle. A water-cooled condenser is provided to condense the solvent vapor, but it cannot reduce the concentration below the dewpoint. Upon completion of the drying cycle, the discharge vent and inlet are opened and fresh air is used to deodorize the clothes. Any remaining solvent is discharged to the atmosphere. The length of the extraction and tumbling cycles should be sufficient to achieve maximum recovery of solvent. When a separate tumbler is used, the extraction cycle should dry the clothes sufficiently to minimize the amount of solvent emitted by evaporation during transfer.

Activated carbon can adsorb 100 percent of the solvent up to the breakpoint; thus, overall efficiency is dependent upon the effectiveness of the collection system, and operation and maintenance programs. Allowing ineffective adsorption techniques, that is, placing the adsorbing unit on line without proper drying and cooling; allowing floor vents to become covered with lint; and allowing ductwork to deteriorate are some examples of poor operation and maintenance.

ABRASIVE BLAST CLEANING

INTRODUCTION

Abrasive blast cleaning is the operation of cleaning or preparing a surface by forcibly propelling a stream of abrasive material against the surface. Blast cleaning operations may be classified according to: (1) The abrasive material used, (2) the method of propelling the abrasive, and (3) the equipment used to control the abrasive stream or move the articles being cleaned into the abrasive stream.

Abrasive Materials

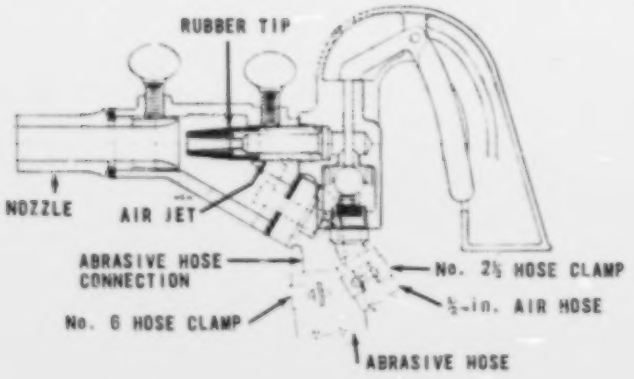
Silica sand has been used longer than any other material, principally because of its ready availability and low cost. It has a rather high breakdown rate, but is still widely used where reclaiming the abrasive is not feasible. Synthetic abrasives, such as silicon carbide and aluminum oxide, are sometimes used as a substitute for sand in special applications. Extremely fine sand and talc are used in a water suspension for fine finishing. Soft abrasives such as ground corn cobs, cereal grains, and cracked nut shells are used to clean without removing any metal. Metallic abrasives are made from cast iron and steel (Stine, 1955).

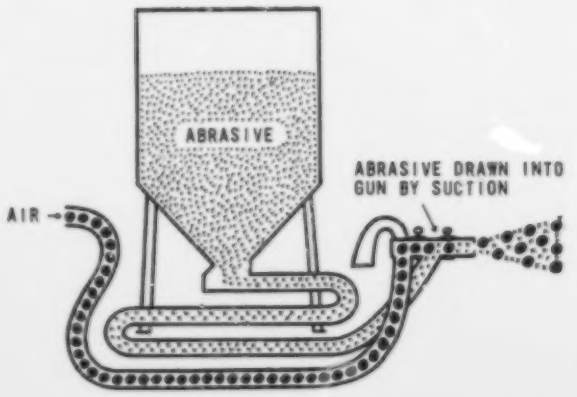
Cast iron shot is made by spraying molten cast iron into a water bath. The shot is hard and brittle, but its breakdown rate is only 2.5 percent that of sand. Cast iron grit is made by crushing the oversize and irregular particles formed when cast iron shot is being made. The sharp edges of the grit give it a very rapid cutting action. The breakdown of the hard, brittle particles continually exposes new cutting edges. Annealed shot is made from special-alloy cast iron and is heat treated to reduce its brittleness. Its breakdown rate is only one-third to one-half that of cast iron shot or grit. Steel shot is produced by blowing molten steel. It is not as hard as cast iron shot but is much tougher. Its breakdown rate is only about one-fifth that of cast iron shot.

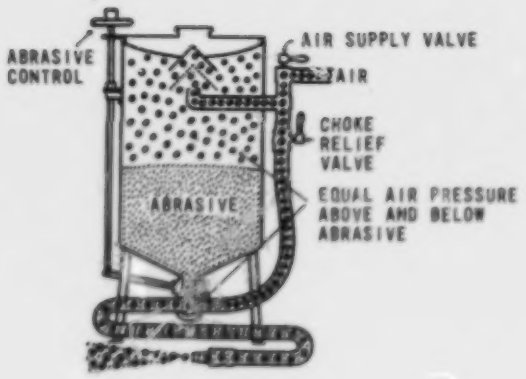
Method of Propelling the Abrasive

Three means of propelling the abrasive are compressed air, high-pressure water, and centrifugal force.

Two types of compressed-air blasting machines used are suction blast and direct-pressure blast. The suction method uses two rubber hoses connected to a blasting gun. One of the hoses is connected to the compressed-air supply, and the other is connected to the bottom of the abrasive supply tank, whose top is open. The gun, as shown in Figure 291 (top left), consists of a casting with an air nozzle that discharges into a larger nozzle. The abrasive hose is attached to the chamber between the nozzles. The high-velocity air jet, expanding into the larger nozzle, creates a partial vacuum (12 to 17 inches mercury) in the chamber, and the abrasive is drawn in and expelled through the discharge nozzle. In the direct-pressure types, as shown in Figure 291 (bottom left), the abrasive supply tank is a pressure vessel with the compressed-air line connected to both the top and bottom discharge line. This permits abrasive to flow by gravity into the discharge hose without loss of pressure. Direct-pressure machines propel from 2 to 4 times as much abrasive per cubic foot of air (at equal pressures) as suction-type machines do, but the cost of the suction machines is less. Compressed air is also used in wet sandblasting. In a specially designed direct-pressure machine, as shown in Figure 291 (bottom right), the abrasive supply tank is flooded with water, and a mixture of sand and water is propelled by the compressed







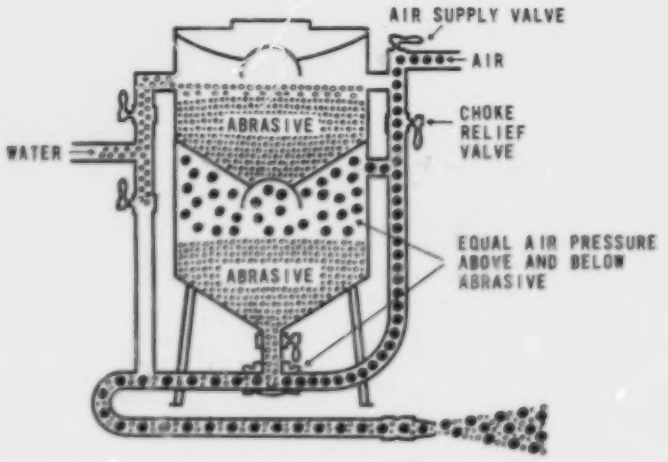


Figure 291. Types of compressed-air blasting machines: (top left) Suction gun, (top right) suction-type blasting machine, (bottom left) direct-pressure blasting machine, (bottom right) wet blasting machine (Bulletin No. 100B, Pangborn Corporation, Hagerstown, Md.).

air. Wet sandblasting can also be accomplished by attaching a special nozzle head with a water hose to the nozzle of a direct-pressure machine as shown in Figure 292.

In hydraulic blasting, the propulsive force is high-pressure water. A mixture of water and sand is propelled through a nozzle with great force by a pump that develops a pressure of 1,000 to 2,000 psi. Sand reclamation is usually practiced in these systems. Figure 293 is a diagram of a complete hydraulic blasting system. Equipment such as this is used for core knockout and for cleaning very large castings, heat exchanger tube bundles, and other large pieces of equipment.

Centrifugal force is the third method of propelling abrasive. Abrasive is fed to the center of a rotating impeller, slides along spoke-like vanes, and is discharged with great force in a controlled pattern. Figure 294 shows one type of abrasive impeller. Metallic abrasives are used with this type of equipment.

Equipment Used to Confine the Blast

The oldest and most widely used device to confine and control the blast is the blasting room, which consists of an enclosure with the operator inside manipulating the blast from a hose. Blasting rooms vary widely in their construction. One popular design is the all-steel, prefabricated room with floor grating and a completely automatic abrasive recovery system. These rooms usually use metal grit or shot and often have monorail conveyors, rail cars, or rotating tables to aid the operator in handling the objects, which are usually large and heavy. Less desirable designs, but sometimes adequate, are makeshift rooms of wooden construction used for infrequent sandblasting operations.

For cleaning small parts, the blasting cabinet is frequently used. A blasting cabinet consists of a relatively small enclosure with openings to which are attached long-sleeved rubber or canvas gloves by which the operator, from outside the cabinet,

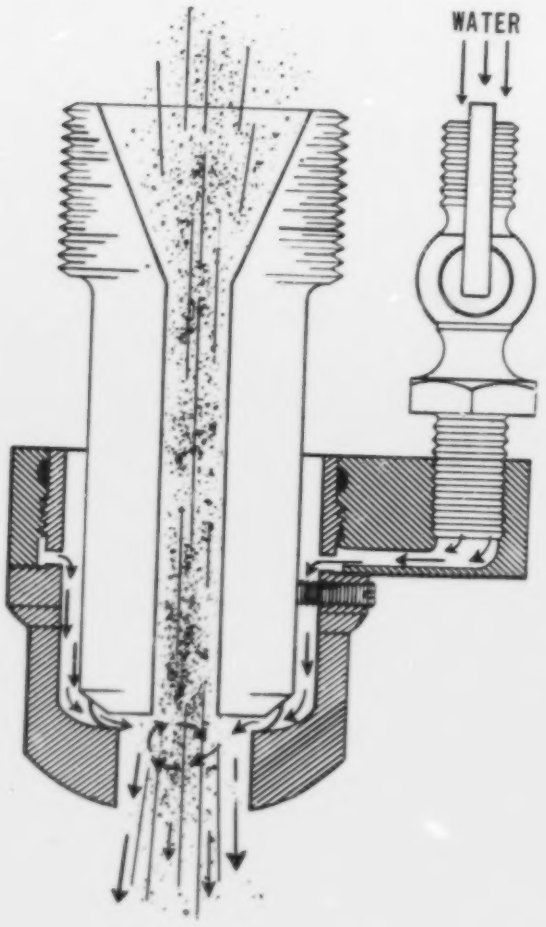


Figure 292. Adapter nozzle that converts dry sandblasting to wet sandblasting (Sanstorm Manufacturing Co., Fresno, Calif.).

manipulates the blasting gun and objects to be abrasive blasted, as depicted in Figure 295. All types of abrasives are used in cabinets--sand, metallics, soft abrasives, and slurries.

Centrifugal impellers are usually incorporated into a machine that handles the objects so as to expose all surfaces to the blast. The two most common types are those using tumbling action and those containing rotating tables, as shown in Figures 296 and 297. Special machines are made for specific jobs, such as cleaning sheet metal strip. The housing of these machines confines the blast and its effects. Automatic abrasive recovery and recycle equipment are used.

Another machine consists of a perforated drum or barrel rotating inside a cabinet. A blast gun is mounted so as to project through one end of the drum. Tumbling action exposes all parts of the objects to the blast. Both sand and metallic abrasives are used. Abrasive-recycling equipment is usually provided.

THE AIR POLLUTION PROBLEM

The amount of dust created by abrasive blast cleaning varies widely with the abrasive used, parts being cleaned, and propelling medium. Dry sandblasting produces large dust concentrations as a result of breakdown of the sand. Metallic abrasives, of course, produce less dust but can produce heavy concentrations in cleaning such things as castings with considerable amounts of adhering sand. The

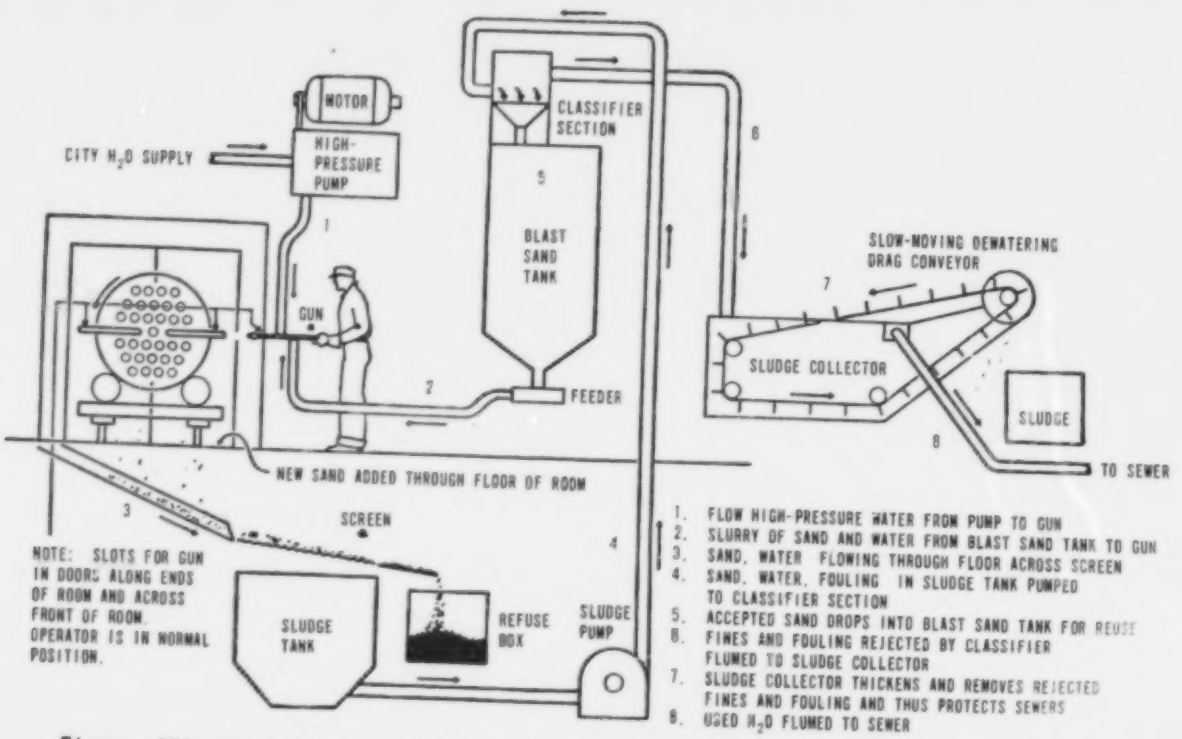

MOTOR
CLASSIFIER SECTION
CITY H_2O SUPPLY
HIGH-PRESSURE PUMP
BLAST SAND TANK
SLOW-MOVING DEWATERING DRAG CONVEYOR
GUN
FEEDER
SLUDGE COLLECTOR
SLUDGE
TO SEWER
NEW SAND ADDED THROUGH FLOOR OF ROOM
SCREEN
NOTE: SLOTS FOR GUN IN DOORS ALONG ENDS OF ROOM AND ACROSS FRONT OF ROOM. OPERATOR IS IN NORMAL POSITION.
SLUDGE TANK
REFUSE BOX
SLUDGE PUMP
1. FLOW HIGH-PRESSURE WATER FROM PUMP TO GUN
2. SLURRY OF SAND AND WATER FROM BLAST SAND TANK TO GUN
3. SAND, WATER FLOWING THROUGH FLOOR ACROSS SCREEN
4. SAND, WATER, FOULING IN SLUDGE TANK PUMPED TO CLASSIFIER SECTION
5. ACCEPTED SAND DROPS INTO BLAST SAND TANK FOR REUSE
6. FINES AND FOULING REJECTED BY CLASSIFIER FLUMED TO SLUDGE COLLECTOR
7. SLUDGE COLLECTOR THICKENS AND REMOVES REJECTED FINES AND FOULING AND THUS PROTECTS SEWERS
8. USED H_2O FLUMED TO SEWER

Figure 293. Hydraulic blasting system (Pangborn Corporation, Hagerstown, Md.).

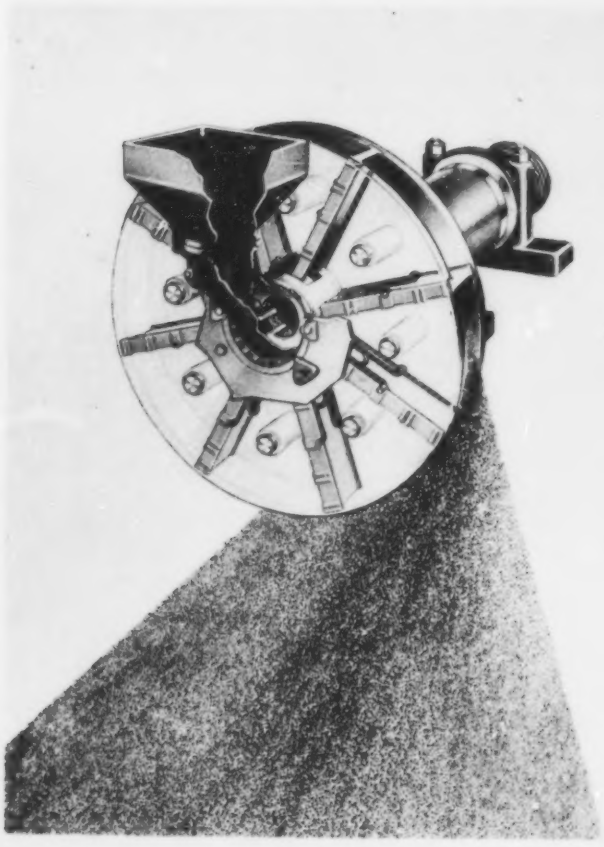


Figure 294. Centrifugal impeller for metallic abrasives (Wheelabrator Corporation, Mishawaka, Ind.).

Figure 295. Blasting cabinet (Pangborn Corporation, Hagerstown, Md.).

dust concentration is small during wet blasting or when metallic abrasives are used for tasks such as removing welding and for heat treating scale.

HOODING AND VENTILATION REQUIREMENTS

The structures previously described to control the blast act as hoods, and exhaust ducts are attached to them for ventilation.

Blast cleaning rooms are ventilated by baffled inlet openings, usually in the roof, and exhausted from near the floor. Recommended ventilation rates vary from 60 to 100 fpm across the floor area with 80 fpm the usual choice (Industrial Ventilation, 1960). These rates are based mainly on the maintenance of visibility in the room. The usual requirement for dust control is an indraft velocity of at least 500 fpm through all openings (ibid). By making the openings small, a small exhaust volume suffices to meet the requirement, but visibility is so poor during sandblasting as to impair the operator's effectiveness seriously. Health codes require that the operator wear an air-supplied, Bureau of Mines approved abrasive blasting helmet.

The ventilation requirement for blast cabinets is similar to that for blasting rooms. Twenty air changes per minute are usually recommended, based primarily on the maintenance of visibility. Even during wet sandblasting, this exhaust rate is usually required for maintenance of visibility.

For blasting barrels, rotary tables, and tumbling-type machines, the general rule of 500 fpm indraft velocity at all openings is applicable. The total area of openings of some machines is difficult to measure; however, the manufacturer usually specifies the required ventilation rate. This rate includes sufficient airflow to remove excess fines so as to maintain the abrasive in an optimum condition.

AIR POLLUTION CONTROL EQUIPMENT

For dust of such widely varying concentration and particle size as is produced in the various blast-

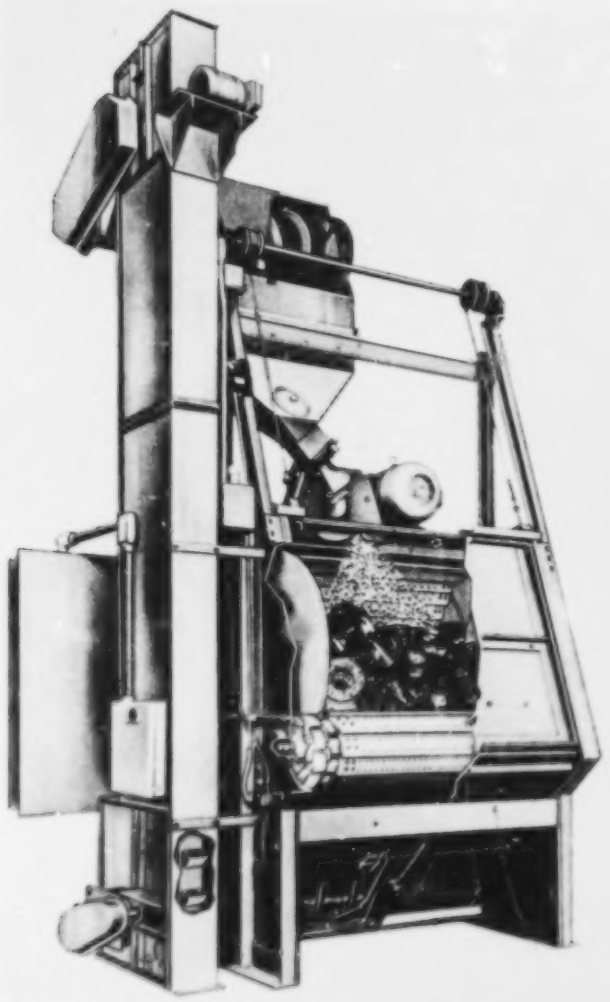


Figure 296. Blast cleaning machine that uses tumbling action (Wheelabrator Corporation, Mishawaka, Ind.).

Figure 297. Blast cleaning machine containing multiple rotary tables (Pangborn Corporation, Hagerstown, Md.).

ing operations, the baghouse is the most widely used type of collector. The positive collection mechanism of the baghouse ensures virtually 100 percent collection efficiency for an adequately sized unit in good condition. The filtering velocity should not exceed 3 fpm. Standard cotton sateen cloth bags are adequate for this service. Since virtually all blast cleaning operations are intermittent, a noncompartmented baghouse can be considered.

A scrubber of good design collects the bulk of the dust, and wet collectors are used to some extent. A scrubber of high power input is, however, required for collecting the very fine dust.

Wet sandblasting does not require collection equipment and provides a means of blast cleaning buildings, bridges, and other structures without creating a dust nuisance. Collecting the dust from dry sandblasting of structures such as these would be very difficult or impossible.

ZINC-GALVANIZING EQUIPMENT

INTRODUCTION

Zinc galvanizing may be defined as the art of coating clean, oxide-free iron or steel with a thin layer of zinc by immersion in molten zinc held at temperatures of 840° to 860°F (Elliott et al., 1961). In order to achieve optimum results, the fundamental processing steps to be followed are:

1. Degreasing in a hot, alkaline solution;
2. rinsing thoroughly in a water rinse;
3. pickling in an acid bath;
4. rinsing thoroughly in a water rinse;
5. prefluxing in zinc ammonium chloride solution;
6. immersing the article in the molten zinc through a molten flux cover;
7. finishing (dusting with sal ammoniac to produce smooth finishes).

When considering the air pollution aspects of the galvanizing operation, one might be inclined to omit the first five steps because they do not normally produce excessive air contaminants. Improper degreasing does, however, increase the generation of air contaminants when the article is immersed in the hot zinc. Moreover, stripping previous zinc coatings in the pickling tanks causes excessive acid mists to be generated.

Cleaning

If an article is not thoroughly degreased, an oil mist is discharged when the article is dipped into the molten zinc. If the articles are not properly pickled and rinsed, more flux must be used to

achieve the desired coating, which in turn creates more fumes. It is important, therefore, to degrease, pickle, and rinse thoroughly the articles being galvanized, not only to obtain a good zinc coating, but also to reduce the generation of fumes and facilitate the collection of unavoidable fumes.

Cover Fluxes

On the assumption that the article was properly prepared for dipping in the molten zinc, a flux must still be used to remove the oxide film that forms as the article is being transported from the last rinse tank to the galvanizing kettle. To exclude air from the part after fluxing, the flux is floated on the zinc surface so that the article is fluxed as it enters the zinc. Figure 298 shows the flux cover on one end of a galvanizing kettle.

The flux is thought to create most of the air contaminants from a galvanizing operation; therefore, a description of fluxes, their composition and action is of value. The theory is that, regardless of whether ammonium chloride or zinc ammonium chloride is used, the composition of the usable flux cover is molten zinc chloride in which ammonium chloride is absorbed and ammonia and hydrogen chloride gases are trapped. The active cleaning agent is the hydrogen chloride gas formed by the dissociation of ammonium chloride due to heat. Zinc chloride is present either because it was placed there with the ammonium chloride or because of the reaction of hydrogen chloride with the molten zinc. The zinc chloride is necessary to maintain the active ingredient on the zinc surface.

To form a flux cover, either ammonium chloride or, preferably, zinc ammonium chloride is placed on the molten zinc surface. Usually a foaming agent such as glycerine is added to the flux before it is applied to the kettle. If ammonium chloride is used, the heat from the zinc causes the salt to decompose and form hydrogen chloride and ammonia gases. Both gases tend to rise and escape from the kettle where they cool and recombine to form a fume of ammonium chloride. Because the hydrogen chloride and zinc are very reactive, they form zinc chloride, which remains on the zinc as a liquid at the temperature of the zinc bath. Since only part of the hydrogen chloride is used up in this reaction, the fumes escaping contain an excess of ammonia. As more ammonium chloride is added to the zinc surface, the zinc chloride that is formed begins to absorb it. At the same time a foam filled with hydrogen chloride and ammonia gases is formed. The foaming agent increases the depth and fluidity of the foam. If foaming-type zinc ammonium chloride is used as a starting material, the zinc chloride merely melts, trapping the bulk of the gases formed, and retards the deposition of the ammonium chloride. The flux cover is made much more easily and with less fuming when the foaming-type zinc ammonium chloride is used in place of ammonium chloride.

The flux cover has a number of important functions in addition to the cleaning action already mentioned. It serves as a preheating and drying medium to reduce spattering or explosions in the molten zinc, and distortion of thin metal sections. It keeps the zinc surface free of oxides, which, if occluded in the coating, tend to dull it and retard drainage of zinc from the work. Heat losses from the kettle are also reduced.

Foaming Agents

If galvanizing is done with a thin layer of molten flux, a higher temperature is reached throughout the flux layer that induces fuming and loss of flux ingredients. The flux becomes viscous and inactive in a short period of time, requiring frequent additions of fresh flux to keep it in prime condition. The thin molten flux cover can be fluffed up by additions of foaming agents such as glycerine, wheat bran, wood flour, sawdust, and others. The resulting deep-foaming type of flux cover has the advantage of reducing the quantity of objectionable fumes. Some other advantages are longer flux life, greater ease of control in maintaining fluidity and fluxing activity, reduction of zinc spattering, and saving of flux, zinc, and heat.

To achieve the required foaming action, a small but definite amount of foaming agent is added to the flux. Too little or too much accelerates the rate at which the flux becomes too viscous. To reduce the amount of fuming, the foaming agent should be mixed with the flux before the flux is placed on the surface of the zinc bath. Of the foaming agents mentioned, glycerine seems to be the most efficient. Observations of the fuming tendencies of various proprietary foaming-type fluxes have shown that some fume more than others. The compositions of the proprietary foaming agents have not been revealed by the manufacturers.

Dusting Fluxes

After an article to be galvanized has been charged into the kettle through the flux cover, and while it is still completely immersed in the zinc bath, it is moved to a portion of the kettle where it can be re-

moved through a clean zinc surface (see Figure 298). If the articles are small, such as bolts, nuts, nails, and so forth, they are usually dusted with powdered ammonium chloride immediately upon removal from the molten zinc. The dusting flux causes the zinc to flow and results in a smooth, bright finish. The dusting must be done before the work has time to cool off, since the zinc coating must still be molten in order to flow and drain properly from the work. At the temperature of the molten zinc, the flux decomposes generating fumes.

THE AIR POLLUTION PROBLEM

Observations of many galvanizing kettles have revealed that air contaminants are discharged whenever the flux cover is disturbed, fresh flux is added, or galvanized objects are dusted with ammonium chloride.

Flux agitation occurs to some extent each time an object is immersed in the zinc through the flux cover. If the objects are smooth and dry and the agitation is not great, the amount of fuming is small. When the agitation is severe a correspondingly larger amount of fumes is discharged. Mechanical actions that break some of the bubbles making up the flux cover release fume-forming gases.

When fresh flux is placed on the molten metal in a kettle, some time is required for it to form a foaming cover and, during this interval, dense fumes escape. Moreover, when fresh flux is stirred into the existing flux cover, fumes are discharged as a result of the agitation and the time necessary for the fresh flux to be absorbed by and become part of the foam. If the air contaminants were due only to the volatile constituent in the flux, the fumes would consist only of ammonium chloride. Zinc, zinc chloride, and oil, among other materials, have, however, been identified in the particulate matter discharged from galvanizing kettles.

Zinc and zinc chloride have very low vapor pressures at normal galvanizing temperatures, and one would expect neither of them to vaporize to any great extent. The emissions from these materials are believed to be the result of mechanical entrainment, which occurs when wet articles are galvanized. Frequently an object is immersed too rapidly, which permits some of the steam to vent into the molten zinc below the flux cover, the rapidly escaping steam atomizing some zinc and flux into the air.

Cases have been observed where the articles to be galvanized are not cleaned thoroughly of materials that volatilize at the temperature of the molten zinc. In one case, the cleaning and pickling solutions did not remove all the lubricant from chain link fence material. The oil was vaporized and discharged as an oil mist with the fumes from the flux cover. The oil, in fact, formed about half of the fumes discharged. In another case, sulfur was not removed from an object before it was charged to the kettle. The resulting fumes were yellow and much more opaque than would normally be expected.

To obtain brighter, smoother finishes, especially on small items, the items are dusted with finely ground sal ammoniac immediately after being removed from the molten zinc. The items dusted are still at a temperature well above the decomposition temperature of sal ammoniac. Nearly all the flux is, therefore, converted to fumes by the operation. Although only small amounts of dusting fluxes are used, dense fumes are always created.

Physical and Chemical Composition of the Contaminants

The appearance and composition of the fumes discharged from galvanizing operations vary according to the operation being conducted. For example, the galvanizing of nuts, bolts, and other small articles does not create much agitation of the flux cover, and emissions are slight. Some fumes are, however, generated when the articles are dusted with ammonium chloride upon removal from the zinc bath. An analysis of these fumes revealed that essentially only ammonium chloride was present.

When many different articles are galvanized, some disturb the flux and produce more fumes than others. The fumes also contain substantial amounts of compounds other than ammonium chloride. The galvanizing of chain link fence material continuously agitates the flux cover and results in a continuous discharge of fumes from the kettle. The visual appearance of the fumes as they are discharged into the air from the various operations is the same--that of light gray smoke. Even under a microscope the fumes from the various sources have the same appearance. Figure 299 is a photomicrograph of a sample of the fumes, indicating that the average particle size is approximately 2 microns.

Under some circumstances the fumes may have different characteristics, but these are attributed to the influence of additional contaminants. For example, Table 115 shows the comparison of the catch from an electric precipitator serving a chain link fencing process kettle with the catch of a baghouse serving a job shop kettle.

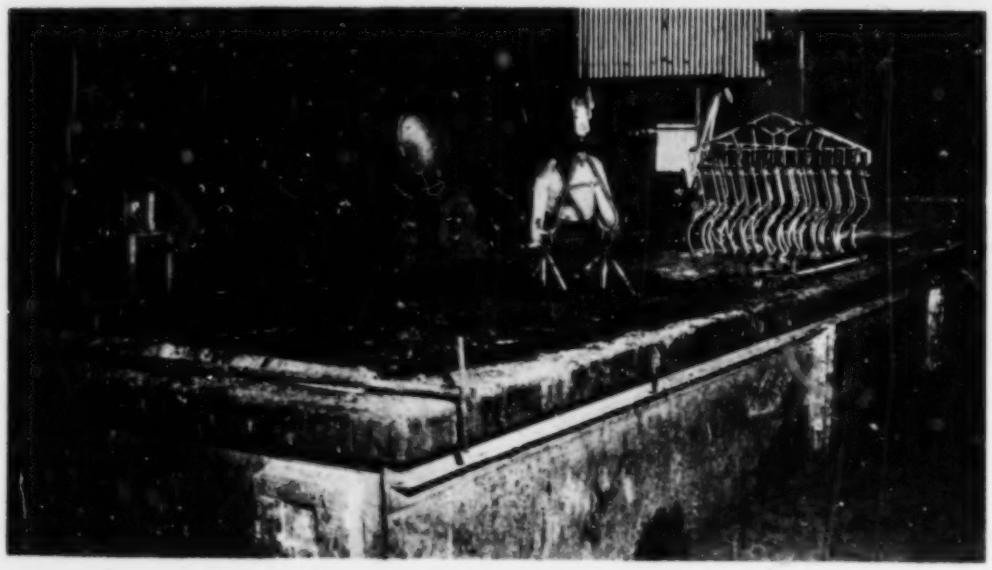


Figure 298. Removing work through a clean zinc surface. Flux cover in foreground (Los Angeles Galvanizing Co., Huntington Park, Calif.).

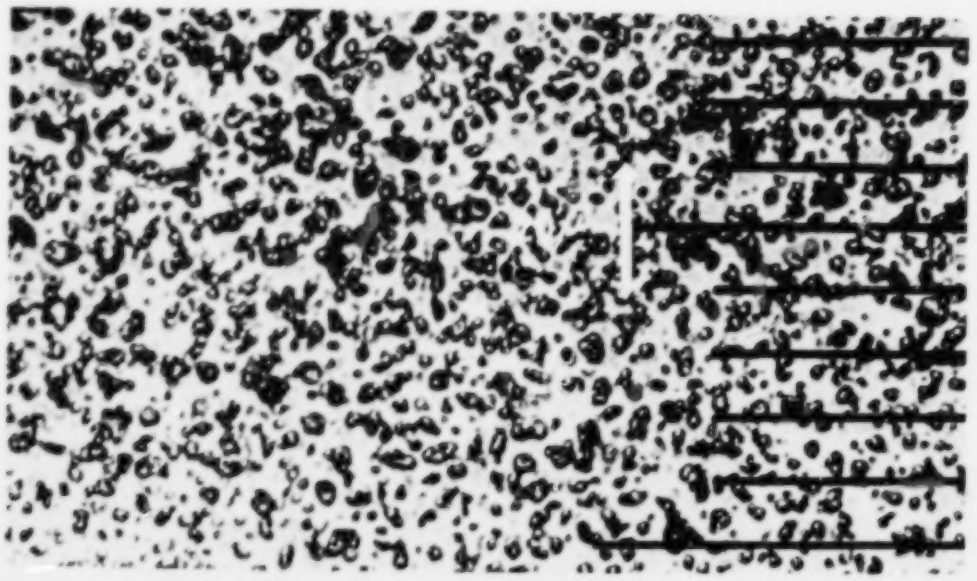


Figure 299 Photomicrograph of fumes discharged from a galvanizing kettle.

The material collected by the baghouse was dry and powdery, but it did agglomerate and was difficult to shake from the bags with ordinary bag-shaking procedures. The material taken from the precipitator was sticky and had the general appearance of thick grease. Table 115 shows that the fumes are different chemically, which explains their different appearance after being collected. The oil in the fumes collected by the precipitator undoubtedly came from a film of oil on the chain link fence material that was vaporized as the fence material was charged into the hot zinc.

HOODING AND VENTILATION REQUIREMENTS

In order to control the emissions from a galvanizing kettle, the fumes generated must be conducted to an efficient control device. In job shops, the headroom needed makes necessary the use of either high-canopy or room-type hoods as shown in Figures 300 and 301. The amount of ventilation volume required with high-canopy hoods increases considerably with the height of the hood; therefore, the size of the collector must be large enough to accommodate the large volumes required.

Slot hoods are used only when the area of fume generation is small, such as the flux box of a chain link fence-galvanizing kettle shown in Figure 302. The slot velocities needed to overcome the thermal draft for the entire surface of a large kettle are high, and large air volumes cool the surface of a zinc bath. This cooling effect creates problems in applying a good zinc coating and increases fuel consumption. When a slot hood can be used, the amount

Table 115. CHEMICAL ANALYSES OF THE FUMES COLLECTED BY A BAGHOUSE AND BY AN ELECTRIC PRECIPITATOR FROM ZINC-GALVANIZING KETTLES

Component	Fumes collected in a baghouse (job shop kettle), wt %	Fumes collected in a precipitator (chain link galvanizing), wt %
NH_4Cl	68.0	23.5
ZnO	15.8	6.5
$ZnCl_2$	3.6	15.2
Zn	4.9	-
NH_3	1.0	3.0
Oil	1.4	41.4
H_2O	2.5	1.2
C	2.8	-
Not identified	-	9.2

Figure 301. Opening to a room-type hood over a galvanizing kettle (Los Angeles Galvanizing Co., Huntington Park, Calif.).

Figure 300. High-canopy hood over a galvanizing kettle (Superior Pacific Galvanizing Company, Inc., Los Angeles, Calif.).

of ventilation required is smaller than that required with high-canopy hoods, and control devices are correspondingly smaller.

Low-canopy hoods can be used on a kettle when headroom is not required. These hoods permit lower ventilation rates for adequate fume capture, and smaller control devices can be used.

AIR POLLUTION CONTROL EQUIPMENT

To collect fumes having particle sizes of 2 microns or less requires a high-efficiency collector such as a baghouse or an electrical precipitator. A baghouse can be used for any galvanizing operation where the air contaminants do not contain oil mists. When an oil mist is present a precipitator should be used.

Several scrubbers, similar to the one shown in Figure 303, have been installed in attempts to control the emissions from galvanizing kettles, but all have been unsatisfactory. Stack analyses disclosed that the amount of fumes collected by these scrubbers was negligible. In each of the scrubbers the contaminated gases were conducted around baffles, through water sprays, and finally, through

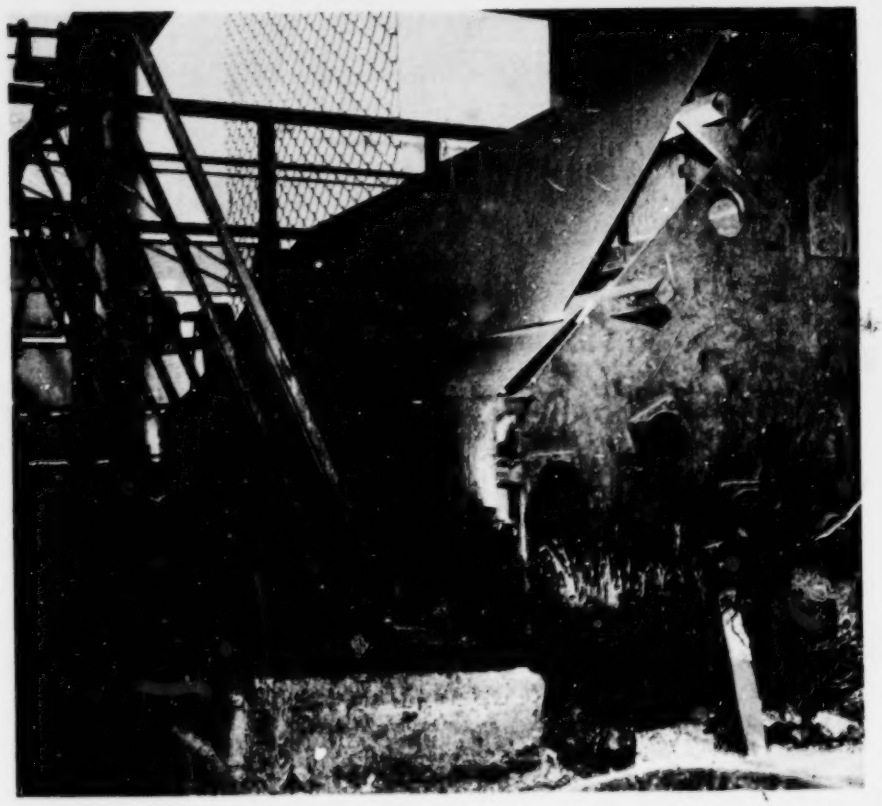


Figure 302. Slot-type hood serving a chain link fence-galvanizing flux box (Anchor Post Products, Inc., of California, Whittier, Calif.).

Figure 303. Water-wash scrubber serving a continuous chain link galvanizing kettle.

mist eliminators. Water was recirculated through the scrubbers with only sufficient makeup to replace the amount lost due to evaporation and mist discharge. The water pressure at the spray heads was approximately 25 psig in each scrubber.

Baghouses

Cotton cloth bags have been found to be an effective filtering medium for baghouses serving the fumes discharged from most galvanizing operations. Neither the fumes nor the gases discharged are deleterious to cotton, nor are they corrosive to the baghouse shell. Because of the large volume of air needed to capture the air contaminants, the temperature of the gases is well below the 180°F limit of cotton bags.

The fumes have a tendency to agglomerate, enhancing filtration; however, they also cling to the bags, making difficult the cleaning of the bags by mechanical shakers. The filtering velocity has a marked effect on the tenacity of the fumes. Only mechanical shaking was found necessary with a filter velocity of 1 fpm. With from 2- to 3-fpm velocities, the bags had to be shaken mechanically at 2-hour intervals, and then every 2 weeks each bag had to be vigorously shaken by hand. With filter velocities in excess of 3 fpm, the fumes could not be removed, even with vigorous shaking every 2 or 3 days.

Because low filtering velocities are required for effective filtration, and large exhaust volumes, for adequate fume capture, the baghouse will be large. Figure 304 shows a baghouse with 13,200 square feet of filter area being used to control the fumes discharged from the kettle shown in Figure 300.

The following example shows some of the factors that must be considered in designing a control system for a galvanizing kettle.

Example 32

Given:

A galvanizing kettle, 4 feet wide by 25 feet long by 3 feet high contains molten zinc at a maximum temperature of 860°F. The products of combustion do not mix with the air contaminants from the kettle. The oil and moisture content of the contaminants are assumed to be negligible. The hood configuration is such that one side will be a part of the building wall extending to the floor, and the opposite side will be constructed of sheet metal, extend-

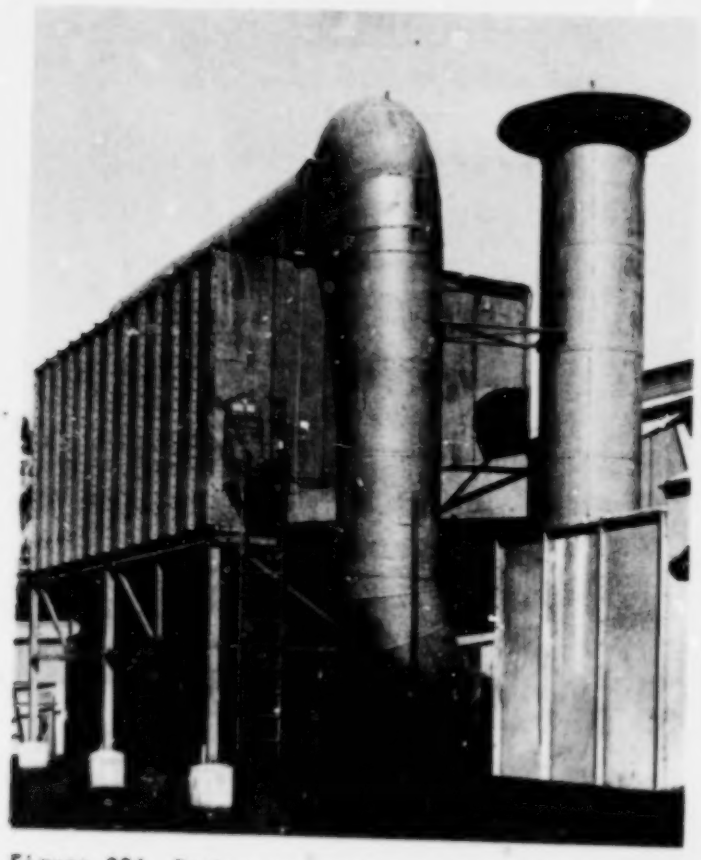


Figure 304. Baghouse serving a galvanizing kettle (Superior Pacific Galvanizing Co., Inc., Los Angeles, Calif.).

ing to within 8 feet from the floor. The ends of the hood must be provided with crane-way access openings 16 feet above the floor.

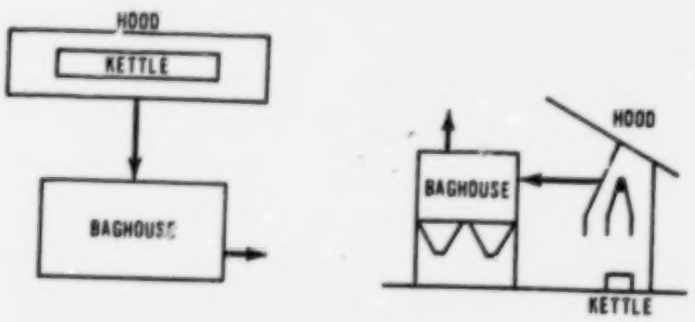


Figure 305. Design of problem presented in example 32.

Problem:

Determine the design features of an air pollution control system using a baghouse.

Solution:

By using the methods described in Chapter 3, the required exhaust rate (Q) can be determined.

The method involves calculating: (1) The heat loss (H) from the process, (2) the hot air induction rate (Q_Z), (3) the dimensions of the column of hot air at the base of the hood, (4) the hood dimensions, (5) the required exhaust rate (Q), and (6) the temperature of the exhaust gases. The sizes of the ductwork, baghouse, and fan can then be calculated.

1. Heat loss from kettle:

For horizontal hot surfaces

$$H' = \frac{0.38}{60} A_s (\Delta t)^{5/4}$$ (from Chapter 3)

A_s = Hot surface area = (4)(25) = 100 ft^2

Δt = Temperature difference between the hot surface and the atmosphere

Assume air temperature to be 70°F

Maximum zinc temperature = 860°F

Δt = 860 - 70 = 790°F

$$H' = \frac{0.38}{60} (100)(790)^{5/4} = 2,660 \text{ Btu/min.}$$

2. Hot air induction rate:

$$Q_Z = 7.4 (Z)^{3/2} (H')^{1/3}$$ (from Chapter 3)

Z = effective height from the hypothetical point source to the base of the hood = Y + 2B

Because of the configuration of the hood, the value of Y is not clear. Although one side of the hood extends to the floor and the other side is 5 feet above the kettle, there will be openings in each end extending to 13 feet above the kettle. To ensure capturing the air contaminants, design for a hood height of Y = 13 feet above the kettle.

The value for B also is not clear. In the derivation of the equation, B is the diameter of the hot surface and is used to calculate the expansion of the column of hot gases arising from the hot surface. The hot surface in this case is rectangular, 4 ft wide by 25 ft long. The expansion of the column of hot gases is due to mixing with cooler air. The cool air mixes from all sides and is motivated by the temperature differential. When the cool air penetrates halfway through the column it meets cool air entering from the opposite side, and thus cancels the driving force. From this it is apparent that the short dimension of the hot-

air column must control the expansion of the column. Therefore, B = 4 feet.

$Z = 13 + (2)(4) = 21$ ft

$$Q_Z = 7.4\ (21)^{3/2}\ (2,660)^{1/3} = 9,800 \text{ cfm.}$$

3. Dimensions of hot gas column at base of hood:

$$D = \frac{(Z)^{0.88}}{2} \quad \text{(from Chapter 3)}$$

D = B (See explanation in Item 2 above)

$$D = \frac{(21)^{0.88}}{2} = \frac{14.6}{2} = 7.3 \text{ ft}$$

Assume that the length will expand the same amount as the width.

Width expansion = 7.3 - 4 = 3.3 ft

Length = 25 + 3.3 = 28.3 ft

Dimensions of hot gas column = 7.3-ft width by 28.3-ft length.

4. Hood dimensions:

Crossdrafts across each hood will be minimized because the sides of the hood are low, extending to the floor on one side and 5 feet above the kettle on the other side. The high openings on each end of the hood could, however, cause crossdrafts, blowing the fumes away from the hood. The hood dimensions should be larger than the dimensions of the rising hot gas stream, the length being extended more than the width. A hood with dimensions of 10 feet wide by 40 feet long should, therefore, be provided.

5. Required exhaust rate:

$Q = Q_Z + VA_f$ (from Chapter 3)

V = velocity of indraft required to keep air moving into all areas of hood.

A_f = hood area not occupied by the entering hot gas current.

Design for V = 100 fpm

$A_f = (10 \times 40) - (7.3 \times 28.3) = 400 - 206 = 194 \text{ ft}^2$

$Q = 9,800 + (100)(194) = 29,200$ cfm

Design for 30,000 cfm.

6. Exhaust gas temperature:

The temperature rise of the air is:

$$\Delta t_a = 58\ \frac{H'}{Q} = 58\ \frac{2,660}{30,000} = 5.1°F$$

Exhaust gas temperature = 75°F.

The temperature rise is not sufficient to affect any of the following calculations, and is, therefore, neglected.

7. Duct diameter between hood and baghouse:

Use recommended velocity of 2,000 ft/min

$$\text{Duct cross-section area} = \frac{30,000}{2,000} = 15 \text{ ft}^2$$

$$\frac{\pi d^2}{4} = 15 \text{ ft}^2$$

$$d = 4.37 \text{ ft}$$

Use a duct diameter of 52-1/2 inches

Note: By using a velocity greater than the minimum, the duct diameter can be decreased to reduce construction costs. Horsepower requirements will, however, be increased.

8. Required filter area of baghouse:

Provide a filtering velocity of 2 fpm

$$\text{Filter area} = \frac{30,000}{2} = 15,000 \text{ ft}^2.$$

9. The exhaust system and fan calculations are made as outlined in Chapter 3. After a system resistance curve is plotted and calculated, a fan is selected whose characteristic curve will intersect the system curve at the required air volume of 30,000 cfm.

Electrical Precipitators

The use of a two-stage, low-voltage-type precipitator, as shown in Figure 306, has been investigated for the control of galvanizing fumes in the Los Angeles area. The investigation led to the use of the precipitator to control fumes containing oil from the flux box of a chain link fence-galvanizing operation. The investigation also revealed that the precipitator could not compete economically with

a baghouse to control the dry and much more dilute fumes captured by a high-canopy hood serving the entire galvanizing kettle.

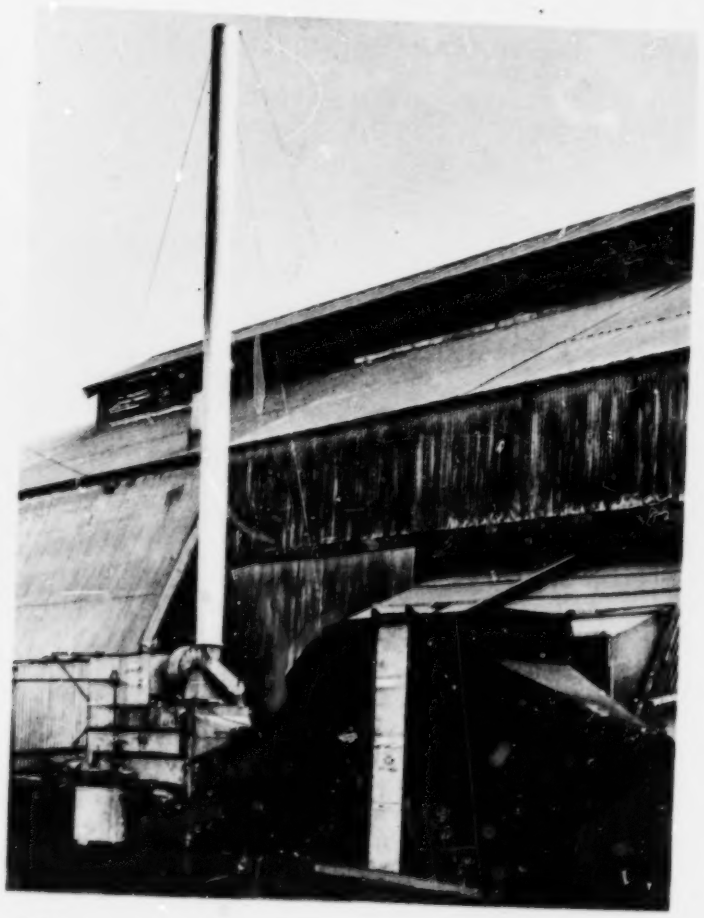


Figure 306. Experimental electric precipitator used in a galvanizing control study (Advance Galvanizing Co., Los Angeles, Calif.).

When only the flux box of a chain link fence-galvanizing operation was vented, the air contaminants consisted of 41 percent by weight oil mist and 59 percent fumes. The concentration of the air contaminants in the exhaust stream was 0.154 grain per scf. With an exhaust gas velocity of 58 fpm through the precipitator, the collection efficiency was 91 percent. With an air contaminant concentration of 0.072 grain per cubic foot and a velocity of 330 fpm through the precipitator, the collection efficiency was 79 percent.

When the entire kettle was vented with the aid of a room-type hood, the air contaminants consisted of 5 percent by weight oil and 95 percent fumes. With an air contaminant concentration in the exhaust gases of 0.0072 grain per scf and a gas velocity of 340 fpm through the precipitator, the collection efficiency was zero. Further tests of the precipitator at lower velocities were not warranted, because at this plant a full-scale precipitator to serve the entire kettle would have to be operated at a velocity of at least 340 fpm to compete economically with a baghouse.

The following example shows some of the factors that must be considered in designing an exhaust system with an electrical precipitator to control the air contaminants discharged from a chain link fence-galvanizing operation.

Example 33

Given:

A chain link fence-galvanizing kettle is provided with a flux box, 10 inches wide by 10 feet long by 1 foot high. Zinc ammonium chloride is used as a cover flux in the flux box. A slot hood is to be used along one side of the flux box to capture the fumes created.

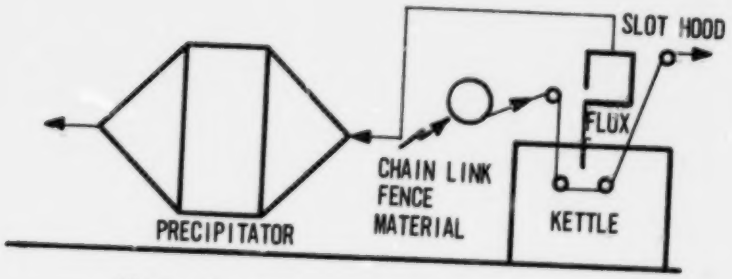


Figure 307. Design of problem presented in example 33.

Problem:

Determine the design features of an air pollution control system using an electrical precipitator.

Solution:

1. Exhaust volume:

   Design for 200 cfm per ft^2 of flux box area

   $$\text{Area} = \frac{10}{12}\ (10) = 8.33\ ft^2$$

   $$(8.33)(200) = 1,666\ \text{cfm}$$

   Design for 1,700 cfm.

2. Slot width:

   Design for a slot velocity of 2,000 fpm

Slot area = $\frac{1,700}{2,000}$ = 0.85 ft^2 = 122.4 $in.^2$

Length = 10 ft = 120 in.

Width = $\frac{122.4}{120}$ = 1.02 in.

3. Diameter of duct from hood to precipitator:

Design for 2,000 fpm

Area = $\frac{1,700}{2,000}$ = 0.85 ft^2

Use 12-1/2-in.-diameter duct.

4. Cross-sectional area of precipitator:

Design for 100 fpm

Area = $\frac{1,700}{100}$ = 17 ft^2.

5. The exhaust system and fan calculations are made as outlined in Chapter 3. After a system resistance curve is plotted and calculated, a fan is selected whose characteristic curve intersects the system curve at the required volume, which in this example, will be 1,700 cfm.

CHAPTER 8

INCINERATION

DESIGN PRINCIPLES FOR MULTIPLE-CHAMBER INCINERATORS

JOHN E. WILLIAMSON, Senior Air Pollution Engineer

GENERAL-REFUSE INCINERATORS

ROBERT J. MAC KNIGHT, Principal Air Pollution Engineer
JOHN E. WILLIAMSON, Senior Air Pollution Engineer

MOBILE MULTIPLE-CHAMBER INCINERATORS

ARTHUR B. NETZLEY, Intermediate Air Pollution Engineer
JOHN E. WILLIAMSON, Senior Air Pollution Engineer

MULTIPLE-CHAMBER INCINERATORS FOR BURNING WOOD WASTE

ARTHUR B. NETZLEY, Intermediate Air Pollution Engineer
JOHN E. WILLIAMSON, Senior Air Pollution Engineer

FLUE-FED APARTMENT INCINERATORS

JOSEPH J. SABLESKI, Air Pollution Engineer*
JOHN E. WILLIAMSON, Senior Air Pollution Engineer

PATHOLOGICAL-WASTE INCINERATORS

PAUL G. TALENS, Air Pollution Engineer

DEBONDING OF BRAKESHOES AND RECLAMATION OF ELECTRICAL EQUIPMENT WINDINGS

ARTHUR B. NETZLEY, Intermediate Air Pollution Engineer
DONALD F. WALTERS, Intermediate Air Pollution Engineer*
JOHN E. WILLIAMSON, Senior Air Pollution Engineer

DRUM RECLAMATION FURNACES

ROY S. BROWN, Air Pollution Engineer
ARTHUR B. NETZLEY, Intermediate Air Pollution Engineer

WIRE RECLAMATION

ARTHUR B. NETZLEY, Intermediate Air Pollution Engineer

*Now with National Center for Air Pollution Control, Public Health Service, U.S. Department of Health, Education, and Welfare, Cincinnati, Ohio.

BLANK PAGE

CHAPTER 8

INCINERATION

DESIGN PRINCIPLES FOR MULTIPLE-CHAMBER INCINERATORS

Disposal of combustible refuse and garbage is one of the most perplexing problems facing urban society today. The greater the population density the more disturbing the problem. This refuse is created by all elements of a community — industry, commerce, and the public.

In the past, disposal of combustible wastes was looked upon as a necessary evil to be accomplished as cheaply as possible. Industrial and commercial installations used a box-like, single-chamber incinerator to burn up to several tons a day. Refuse from apartment houses was generally burned in a chute-fed, single-chamber incinerator. In some areas, especially southern California, each homeowner disposed of his combustible refuse in a backyard incinerator.

During the past 15 years almost every large urban area in the world has experienced a drastic increase in the pollution of its atmosphere. As the discomforts of air pollution became more noticeable, public clamor for rigid regulation of air-contaminating processes increased steadily. In Los Angeles County this led to the banning of open fires and single-chamber incinerators in September 1957. Since that date all incinerators constructed and put into operation in the county have had to meet stringent criteria of performance as well as definite minimum design requirements.

The standards presented in this chapter are tools for creating designs for multiple-chamber incinerators that may be expected to burn rubbish with a minimum discharge of air contaminants. Tabular presentations alone are not sufficient for the best application and understanding of the principles of design involved. Also essential is an understanding of the many factors that created the need for a new approach to incineration and the development of the multiple-chamber incinerator. The design recommendations and supplementary discussions provide answers to many of the questions that confront designers and operators of multiple-chamber equipment. Caution is needed, however, in that only those qualified in combustion equipment design and refractory construction should try to apply the standards presented. Adequacy of design, proper methods of construction, and quality of materials are important to the satisfactory completion of an incinerator that will meet air pollution control requirements and have an average service life expectancy.

In this part of the chapter, the two basic types of multiple-chamber incinerators are compared. Moreover, the principles of combustion, the fundamental relationships for incinerator design, and general design factors are discussed. These data are, for the most part, applicable to other parts of this chapter that discuss incinerators for specific uses.

In addition to discussing incinerators for burning of combustible wood, paper refuse, and garbage, this chapter includes the design of incinerators for the reclamation of steel drums and wire and for debonding of brakeshoes.

The configuration of modern multiple-chamber incinerators falls into two general types as shown in Figures 308 and 309. These are the retort type, named for the return flow of gases through the "U" arrangement of component chambers, and the in-line type, so-called because the component chambers follow one after the other in a line.

RETORT TYPE

Essential features that distinguish the retort type of design are as follows.

1. The arrangement of the chambers causes the combustion gases to flow through 90-degree turns in both lateral and vertical directions.

2. The return flow of the gases permits the use of a common wall between the primary and secondary combustion stages.

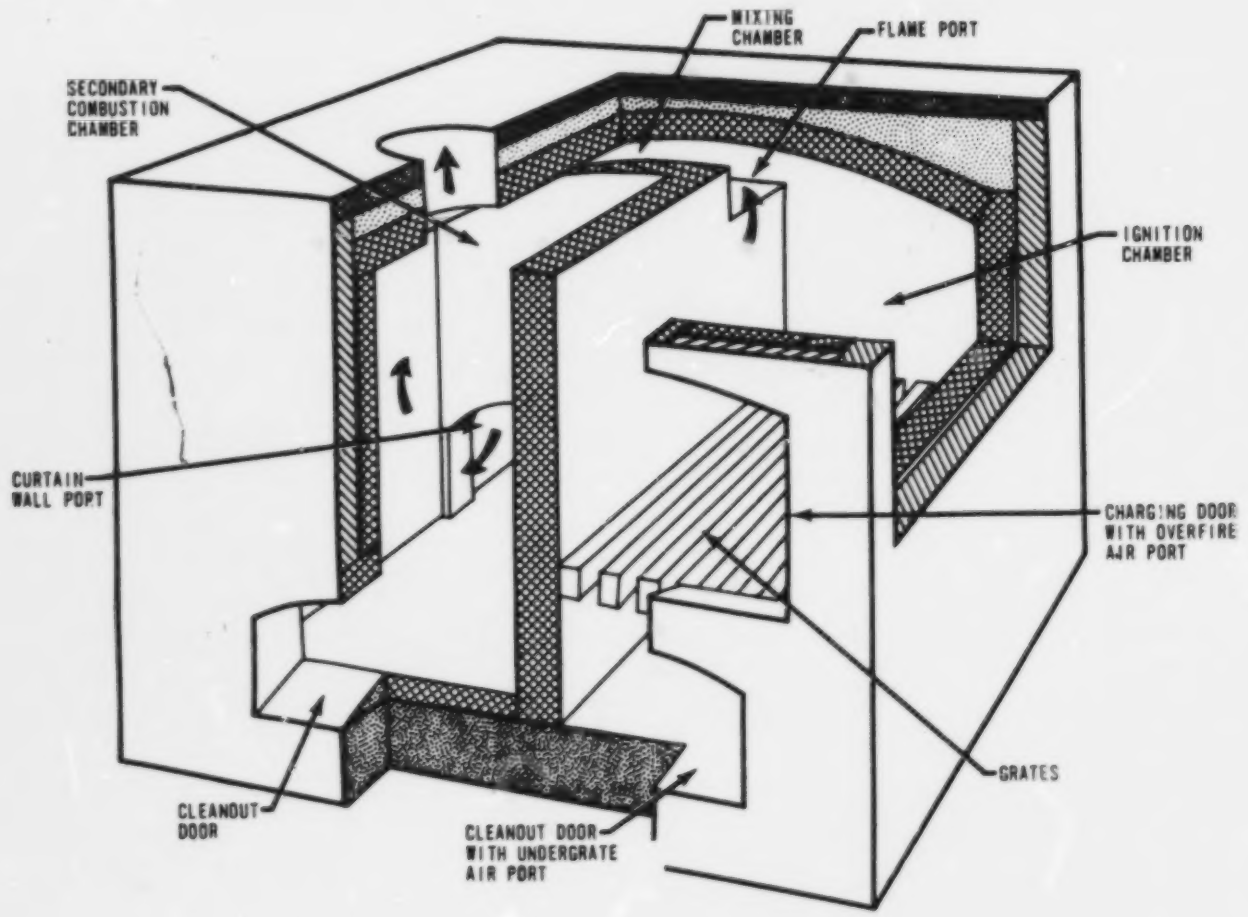
3. Mixing chambers, flame ports, and curtain wall ports have length-to-width ratios in the range of 1:1 to 2.4:1.

4. Bridge wall thickness under the flame port is a function of dimensional requirements in the mixing and combustion chambers. This results in construction that is somewhat unwieldy in the size range above 500 pounds per hour.

IN-LINE TYPE

Distinguishing features of the in-line-type design are as follows.

1. Flow of the combustion gases is straight through the incinerator with 90-degree turns only in the vertical direction.



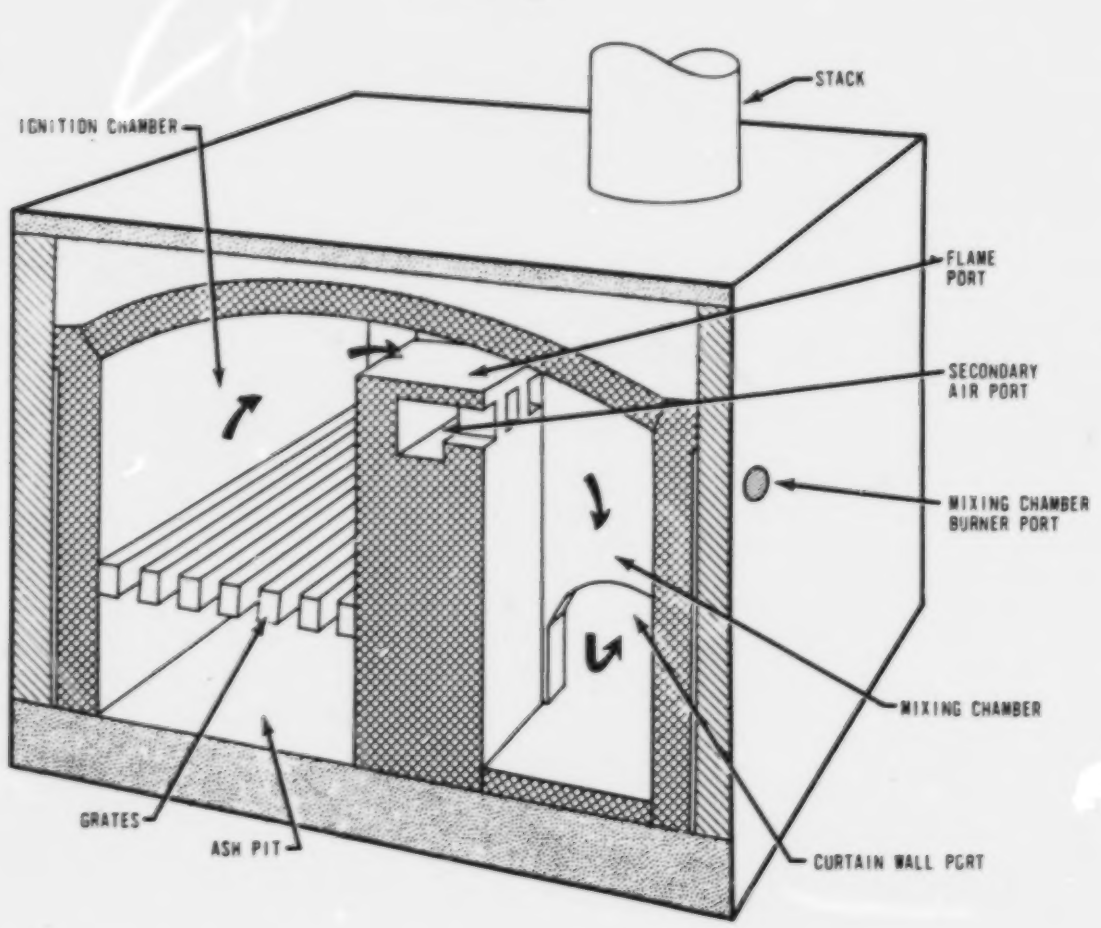


Figure 308. Cutaway of a retort multiple-chamber incinerator.

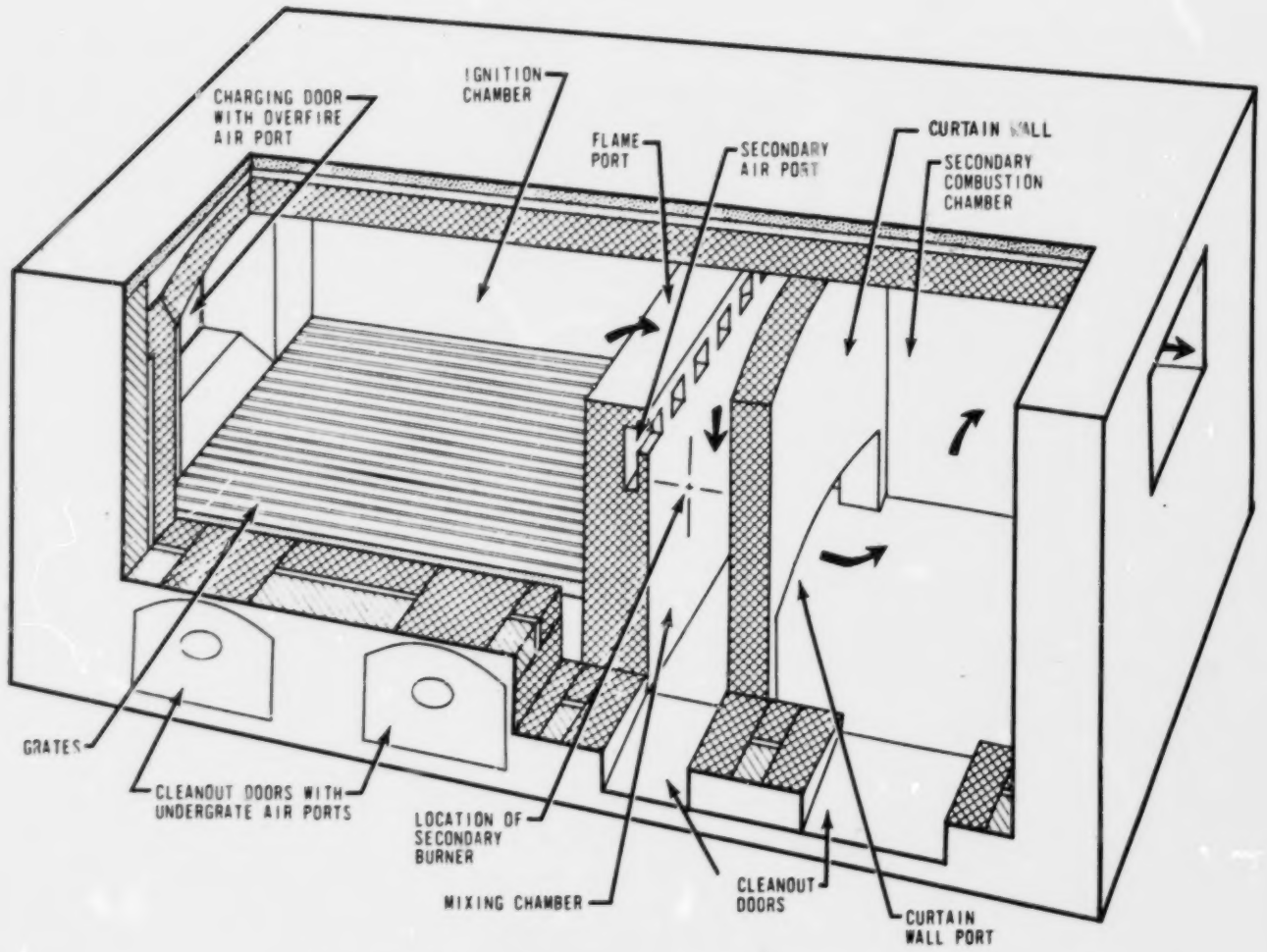


Figure 309. Cutaway of an in-line multiple-chamber incinerator.

2. The in-line arrangement is readily adaptable to installations that require separated spacing of the chambers for operating, maintenance, or other reasons.

3. All ports and chambers extend across the full width of the incinerator and are as wide as the ignition chamber. Length-to-width ratios of the flame port, mixing chamber, and curtain wall port flow cross sections range from 2:1 to 5:1.

DESCRIPTION OF THE PROCESS

The combustion process in a multiple-chamber incinerator proceeds in two stages--primary or solid fuel combustion in the ignition chamber, followed by secondary or gaseous-phase combustion. The secondary combustion zone is composed of two parts, a downdraft or mixing chamber and an uppass expansion or combustion chamber.

The two-stage multiple-chamber incineration process begins in the ignition chamber and includes the drying, ignition, and combustion of the solid refuse. As the burning proceeds, the moisture and volatile components of the fuel are vaporized and partially oxidized in passing from the ignition chamber through the flame port connecting the ignition chamber with the mixing chamber. From the flame port, the volatile components of the refuse and the products of combustion flow down through the mixing chamber into which secondary air is introduced. The combination of adequate temperature and additional air, augmented by mixing chamber or secondary burners as necessary, assists in initiating the second stage of the combustion process. Turbulent mixing, resulting from the restricted flow areas and abrupt changes in flow direction, furthers the gaseous-phase reaction. In passing through the curtain wall port from the mixing chamber to the final combustion chamber, the gases undergo additional changes in direction accompanied by expansion and final oxidation of combustible components. Fly ash and other solid particulate matter are collected in the combustion chamber by wall impingement and simple settling. The gases finally discharge through a stack or a combination of a gas cooler (for example, a water spray chamber) and induced-draft system. Either draft system must limit combustion air to the quantity required at the nominal capacity rating of the incinerator.

DESIGN TYPES AND LIMITATIONS

During the evaluation and development phases of the multiple-chamber incinerator, different incinerator configurations with variations in the sizes and shapes of the several chambers and ports were tested. The results of these tests defined the optimum operating limits for the two basic styles of multiple-chamber incinerators. Each style has certain characteristics with regard to performance and construction that limit its application.

Comparison of Types

The basic factors that tend to cause a difference in performance in the two incinerators are (1) proportioning of the flame port and mixing chamber to maintain adequate gas velocities within dimensional limitations imposed by the particular type involved, (2) maintenance of proper flame distribution over the flame port and across the mixing chamber, and (3) flame travel through the mixing chamber into the combustion chamber.

A retort incinerator in its optimum size range offers the advantages of compactness and structural economy because of its cubic shape and reduced exterior wall length. It performs more efficiently than its in-line counterpart in the capacity range from 50 to 750 pounds per hour. In these small sizes, the nearly square cross sections of the ports and chambers function well because of the abrupt turns in this design. In retort incinerators with a capacity of 1,000 pounds per hour or greater, the increased size of the flow cross section reduces the effective turbulence in the mixing chamber and results in inadequate flame distribution and penetration and in poor secondary air mixing.

No outstanding factors favor either the retort or the in-line configurations in the capacity range of 750 to 1,000 pounds per hour. The choice of retort or in-line configuration in this range is influenced by personal preference, space limitations, the nature of the refuse, and charging conditions.

The in-line incinerator is well suited to high-capacity operation but is not very satisfactory for service in small sizes. The smaller in-line incinerators are somewhat less efficient with regard to secondary stage combustion than the retort type is. In in-line incinerators with a capacity of less than 750 pounds per hour, the shortness of the grate length tends to inhibit flame propagation across the width of the ignition chamber. This, coupled with thin flame distribution over the bridge wall, may result in the passage of smoke from smoldering grate sections straight through the incinerator and out of the stack without adequate mixing and secondary combustion. In-line models in sizes of 750 pounds per hour or larger have grates long enough to maintain burning across their width, resulting in satisfactory flame distribution in the flame port and mixing chamber. The shorter grates on the smaller in-line incinerators also create a maintenance problem. The bridge wall is very susceptible to mechanical abuse since it is usually not provided with a structural support or backing and is thin where the secondary airlanes are located. Careless stoking and grate cleaning in the short-grate in-line incinerators can break down the bridge wall in a short time.

The upper limit for the use of the in-line incinerator has not been established. Incinerators with a capacity of less than 2,000 pounds per hour may be standardized for construction purposes to a great degree. Incinerators of larger capacity, however, are not readily standardized since problems of construction, material usage, mechanized operation with stoking grate, induced-draft systems, and other factors make each installation essentially one of custom design. Even so, the design factors advocated herein are as applicable to the design of large incinerators as to the design of smaller units.

PRINCIPLES OF COMBUSTION

Theoretical treatment of the complex reactions taking place in combustion processes is as yet incomplete, but the empirical art of combustion engineering has developed to an advanced state. The principles of solid-fuel combustion generally apply to incineration processes and include the following.

1. Air and fuel must be in proper proportion.
2. Air and fuel, especially combustible gases, must be mixed adequately.
3. Temperatures must be sufficient for ignition of both the solid fuel and the gaseous components.
4. Furnace volumes must be large enough to provide the retention time needed for complete combustion.
5. Furnace proportions must be such that ignition temperatures are maintained and fly ash entrainment is minimized.

Fluctuation in fuel quality makes satisfactory incinerator design difficult. In addition to wide ranges in composition, wetness, and volatility of fuel, there is diversity in ash content, bulk density, heat of combustion, burning rate and component particle size. All these affect, to some extent, the operating variables of flame propagation rate, flame length, combustion air requirement, and the need for auxiliary heat.

Fundamental relationships for incinerator design were investigated by Rose and Crabaugh (1955) and by the ASME Subcommittee on Incineration Design Standards. The following were studied:

1. The relationship of combustion air distribution to the degree and rate of combustion attained and to the discharge of air contaminants;

2. the relationship of furnace proportions, that is, chambers and ports, to the degree and rate of combustion;

3. the effects of temperature and furnace design on the percentage of acid, volatile organic, and solid contaminants discharged and the percentage of combustibles in the solid contaminants discharged;

4. the relationship of combustion gas velocities to the effects on turbulence and flame travel and to the degree of combustion attained;

5. the relationship of the material burned to the formation of acid and volatile organic compounds.

DESIGN FACTORS

Control of the combustion reaction, and reduction in the amount of mechanically entrained fly ash are most important in the efficient design of a multiple-chamber incinerator. Ignition chamber parameters are regarded as fundamental since solid contaminant discharges can be functions only of the mechanical and chemical processes taking place in the primary stage. Other important factors include the ratios of combustion air distribution, supplementary draft and temperature criteria, and the secondary-combustion-stage velocity and proportion factors. Some of these factors are functions of the desired hourly combustion rate and are expressed in empirical formulas, while others are assigned values that are independent of incinerator size.

Table 116 lists the basic parameters, evaluation factors, and equations for designing multiple-chamber incinerators and gives the minimum values established for each. The allowable deviations should be interpreted with discretion to avoid consistently high or low deviation from the optimum values. Application of these factors to design evaluation must be tempered by judgment and by an appreciation of the practical limitations of construction and economy.

The values determined for the several parameters are mean empirical values, accurate in the same degree as the experimental accuracy of the evaluation tests. The significance of exact figures is reduced further by the fluctuation of fuel composition and conditions. For purposes of design, permissible variations from the optimum mean are plus or minus 10 percent, and velocities may deviate as much as 20 percent without serious consequence.

The formulas governing ignition chamber design were tentatively postulated from data available through tests of units of varying proportions burning at maximum combustion rates. Optimum values of the arch height and grate area may be determined by using the gross heating value of the refuse to be burned and interpolating between the upper and lower curves in Figures 310 and 311. An allowable deviation of these values of plus or minus 10 percent is considered reasonable. Rather than establish formulas for both the upper and lower curves of these figures, which represent 9,000 Btu per pound or more and 7,500 Btu per pound or less, respectively, a formula for the average values of the two curves has been given. This curve corresponds to a gross heating value of 8,250 Btu per pound.

Design Precepts

The ignition mechanism should be one of fuel bed surface combustion. This is attained by the predominant use of overfire combustion air and by charging in such a manner as to attain concurrent travel of both air and refuse with minimum admission of underfire combustion air. Limiting the admission of underfire air and thereby maintaining relatively low fuel bed temperatures is important. With a relatively high air rate through the fuel bed, the stack effluent contains appreciable quantities of metallic salts and oxides in microcrystalline form. A probable explanation is that vapor phase reactions and vaporization of metals take place in high fuel bed temperatures with resultant condensation of particles in the effluent gases as they cool upon leaving the stack.

To accomplish fuel bed surface combustion through use of overfire air, the charging door should be located at the end of the ignition chamber farthest from the flame port, and the fuel moved through the ignition chamber from front to rear. This way, the volatiles from the fresh charge pass through the flames of the stabilized and heated portion of the burning fuel bed. Also, the rate of ignition of unburned refuse is controlled, which prevents flash volatilization with its resultant flame quenching and smoke creation. Top or side charging is considered disadvantageous because of the suspension of dust, disturbance of the stabilized fuel bed, and the additional stoking required.

With good regulation of the burning rate through proper charging, air port adjustment, and the use of an ignition or "primary" burner, the need for

Table 116. MULTIPLE-CHAMBER INCINERATOR DESIGN FACTORS

Item and symbol	Recommended value	Allowable deviation
Primary combustion zone:		
Grate loading, L_G	10 Log R_c; lb/hr-ft^2 where R_c equals the refuse combustion rate in lb/hr (refer to Fig. 310)	± 10%
Grate area, A_G	$R_c \div L_G$; ft^2	± 10%
Average arch height, H_A	4/3 $(A_G)^{4/11}$; ft (refer to Fig. 311)	--
Length-to-width ratio (approx):		
Retort	Up to 500 lb/hr, 2:1; over 500 lb/hr, 1.75:1	--
In-line	Diminishing from about 1.7:1 for 750 lb/hr to about 1:2 for 2,000 lb/hr capacity. Over-square acceptable in units of more than 11 ft ignition chamber length.	--
Secondary combustion zone:		
Gas velocities:		
Flame port at 1,000°F, V_{FP}	55 ft/sec	± 20%
Mixing chamber at 1,000°F, V_{MC}	25 ft/sec	± 20%
Curtain wall port at 950°F, V_{CWP}	About 0.7 of mixing chamber velocity	--
Combustion chamber at 900°F, V_{CC}	5 to 6 ft/sec; always less than 10 ft/sec	--
Mixing chamber downpass length, L_{MC}, from top of ignition chamber arch to top of curtain wall port.	Average arch height, ft	± 20%
Length-to-width ratios of flow cross sections:		
Retort, mixing chamber, and combustion chamber	Range - 1.3:1 to 1.5:1	--
In-line	Fixed by gas velocities due to constant incinerator width	--
Combustion air:		
Air requirement batch-charging operation	Basis: 300% excess air. 50% air requirement admitted through adjustable ports; 50% air requirement met by open charge door and leakage	
Combustion air distribution:		
Overfire air ports	70% of total air required	--
Underfire air ports	10% of total air required	--
Mixing chamber air ports	20% of total air required	--
Port sizing, nominal inlet velocity pressure	0.1 inch water gage	--
Air inlet ports oversize factors:		
Primary air inlet	1.2	
Underfire air inlet	1.5 for over 500 lb/hr to 2.5 for 50 lb/hr	
Secondary air inlet	2.0 for over 500 lb/hr to 5.0 for 50 lb/hr	
Furnace temperature:		
Average temperature, combustion products	1,000°F	± 20°F
Auxiliary burners:		
Normal duty requirements:		
Primary burner	3,000 to 10,000 Btu per lb of moisture in the refuse	
Secondary burner	4,000 to 12,000 Btu per lb of moisture in the refuse	
Draft requirements:		
Theoretical stack draft, D_T	0.15 to 0.35 inch water gage	--
Available primary air induction draft, D_A. (Assume equivalent to inlet velocity pressure.)	0.1 inch water gage	
Natural draft stack velocity, V_S	Less than 30 ft/sec at 900°F	--

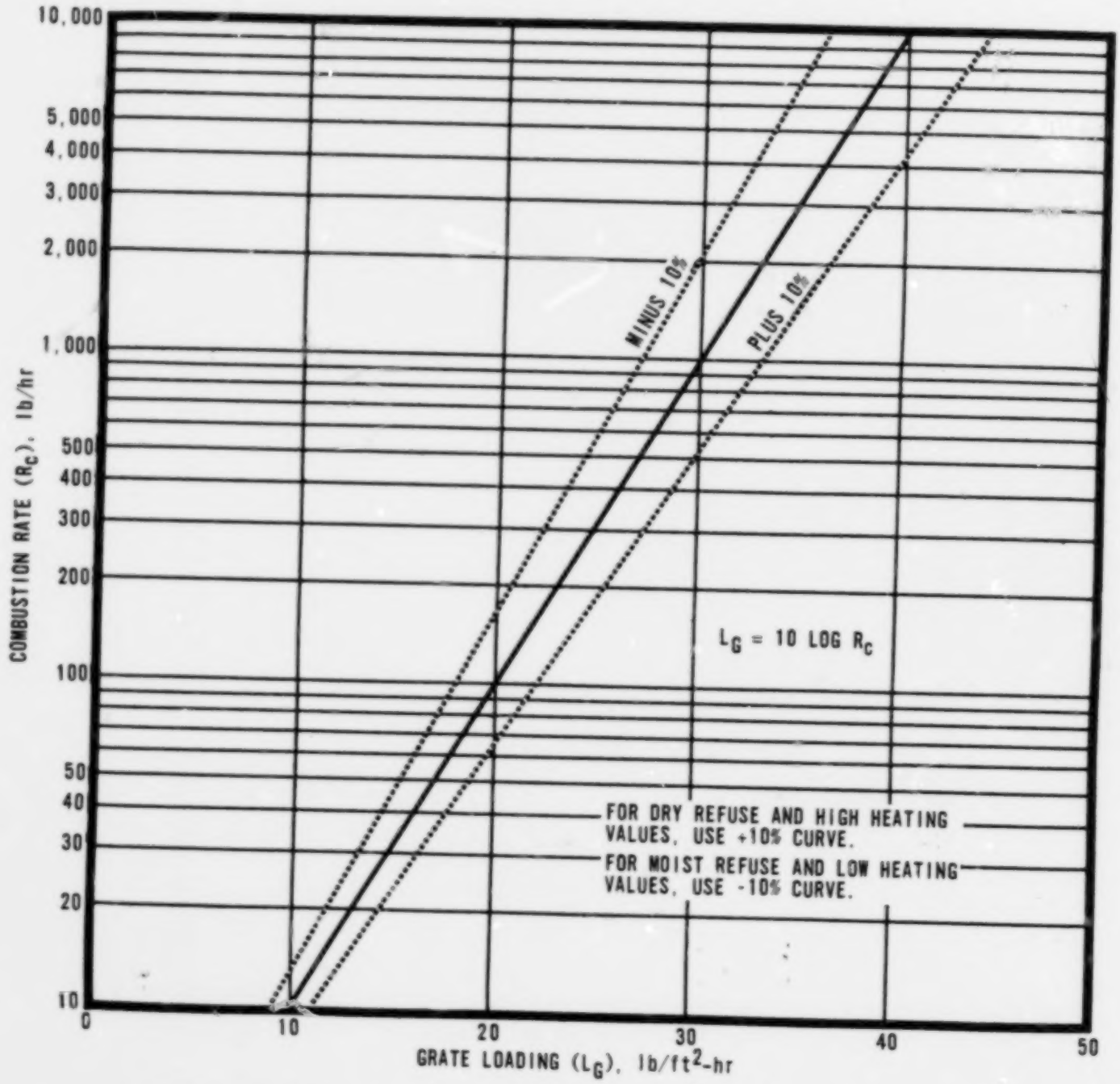


Figure 310. Relationship of grate loading to combustion rate for multiple-chamber incinerators.

stoking can be reduced to that necessary for fuel bed movement before the charging.

Application of the fundamental evaluation precepts combined with admission of secondary air and with trials of various proportions in both chamber and port dimensions established parameters for the mixing and combustion chamber portions of the multiple-chamber incinerator. The primary effect of proper design has been attainment of a higher degree of completion of combustion of volatile and solid combustible effluent components. Designing the combustion chamber as a settling chamber has made possible a reduction in fly ash emissions as well.

GENERAL-REFUSE INCINERATORS

The general refuse incinerators discussed here are used for refuse originating from residences and commercial and industrial establishments. Excluded, however, are the flue-fed, wood-burning, and mobile incinerators, which are discussed individually in other parts of this chapter. General refuse may be defined as combustible refuse such as dry paper or a variable mixture of dry paper and other combustible materials within the following approximate maximum limits (percent of weight): Dry paper (100); wood, scrap (50); shrubbery (30); garbage (30); and sawdust, shavings (10).

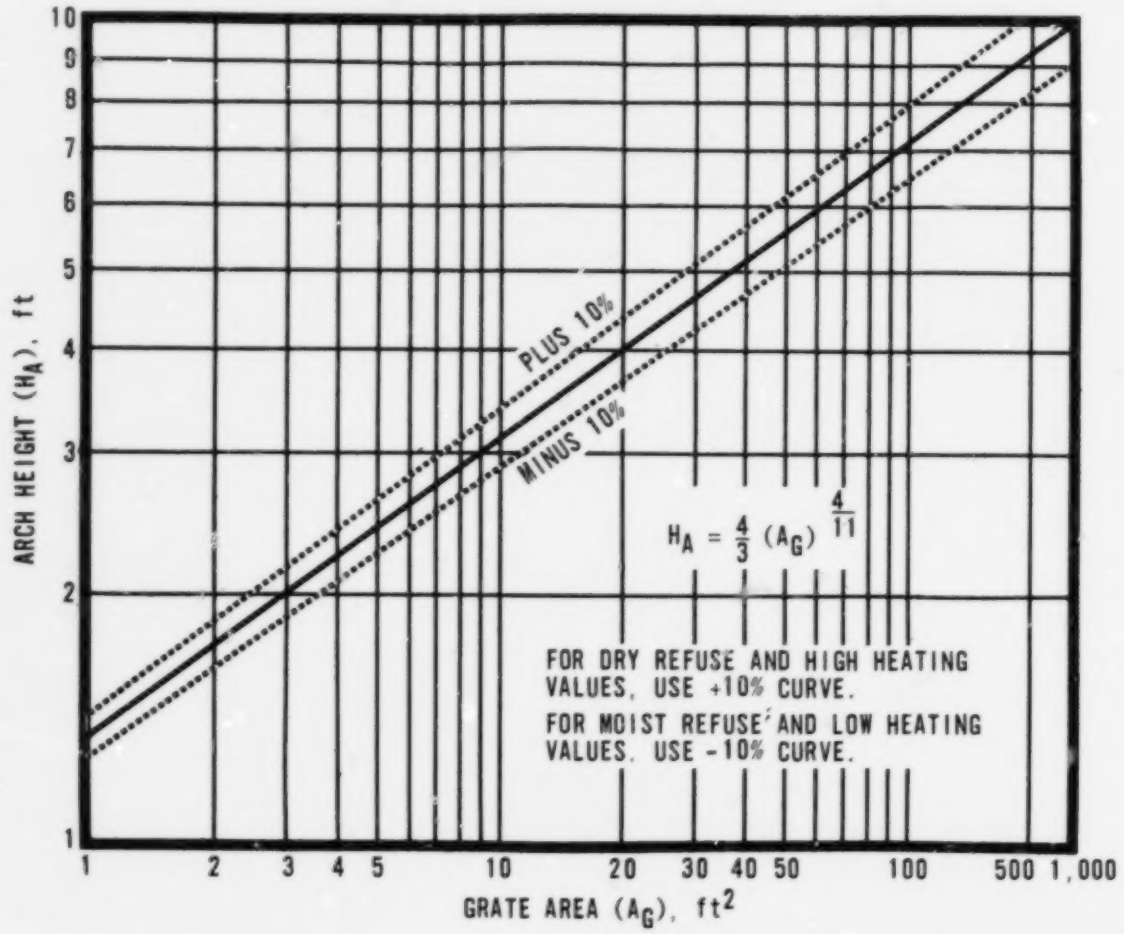


Figure 311. Relationship of arch height to grate area for multiple-chamber incinerators.

Basically, disposal of general refuse may be accomplished by incineration or disposal in a dump. The burning dump that has been used for centuries is rapidly becoming outdated as more and more communities become conscious of air pollution. Other types of incineration range from the use of perforated 55-gallon drums, single-chamber incinerators, and multiple-chamber incinerators to large municipal incinerators. Where land is available, the cut and cover dump represents a more desirable method of waste disposal than municipal incineration from the standpoint both of economics and air pollution control.

THE AIR POLLUTION PROBLEM

The incineration process in general refuse incinerators produces emissions of fly ash, smoke, gases, and odors. Fly ash and odors are undesirable primarily because of their nuisance potential to the occupants of neighboring dwellings and businesses. Smoke and gases, which also have a nuisance potential, contribute to overall air pollution through reduction in visibility and through their ability to enter into smog-forming photochemical reactions in the air.

Since single-chamber incinerators offer the advantage of positive control of combustion air distribution and that of concentration of heat by virtue of enclosing the fire within refractory walls, they are believed to be considerably more effective than an open fire. Even so, single-chamber incinerators have been found to have particulate emissions of from 14 to 35 pounds per ton of material burned. By contrast, the particulate discharges from well-designed multiple-chamber incinerators average 4.5 pounds per ton of refuse burned, which is one-tenth to one-fourth the amount of solid and liquid combustion contaminants emitted from single-chamber units. Average amounts of particulate emissions, as well as of the major gaseous contaminants, from single- and multiple-chamber incinerators are given in Table 117.

AIR POLLUTION CONTROL EQUIPMENT

As always, the best methods of air pollution control are prevention of the creation of air pollutants by disposal of the refuse in landfill projects. The next best means of controlling air pollution from the incineration of general refuse is complete combustion in a multiple-chamber incinerator. The

remainder of this part of the chapter is limited to the design of multiple-chamber incinerators for effective disposal of general refuse with a minimum creation of air pollution.

Table 117. COMPARISON BETWEEN AMOUNTS OF EMISSIONS FROM SINGLE- AND MULTIPLE-CHAMBER INCINERATORS

Item	Multiple chamber	Single chamber
Particulate matter, gr/scf at 12% CO_2	0.11	0.9
Volatile matter, gr/scf at 12% CO_2	0.07	0.5
Total, gr/scf at 12% CO_2	0.19	1.4
Total, lb/ton refuse burned	3.50	23.8
Carbon monoxide, lb/ton of refuse burned	2.90	197 to 991
Ammonia, lb/ton of refuse burned	0	0.9 to 4
Organic acid (acetic), lb/ton of refuse burned	0.22	< 3
Aldehydes (formaldehyde), lb/ton of refuse burned	0.22	5 to 64
Nitrogen oxides, lb/ton of refuse burned	2.50	< 0.1
Hydrocarbons (hexane), lb/ton of refuse burned	< 1	--

DESIGN PROCEDURE

The design factors itemized in Table 116 are the basis for the design of a multiple-chamber incinerator. These factors are used to determine the area of the grate, the average height of the arch, the proportioning of the ignition chamber, the sizing of the gas ports, the cross section of the mixing chamber, the sizes of the inlet air ports, and the other necessary dimensions and proportions. Application of these factors, however, requires that calculations be made to convert the data into usable form. These calculations are illustrated in the problem given at the end of this part of the chapter.

These calculations fall into three general categories: (1) Combustion calculations based upon the refuse composition, assumed air requirements, and estimated heat loss; (2) flow calculations based upon the properties of the products of combustion and assumed gas temperatures; and (3) dimensional calculations based upon simple mensuration and empirical sizing equations. The calculations needed to determine weights, velocities, and average temperatures of the products of combustion are derived from standard calculation procedures for combustion. Average gross heating values and theoretical air quantities are used. Chemical properties and combustion data for the major components of general refuse are given in Table 118. The only omission is shrubbery, which may be safely assumed to have the same composition as average wood.

The average temperature of the combustion products is determined through normal calculations of heat loss. The burning rate and average composition of the refuse are assumed to be constant. When extremes in quality and composition of material are encountered, the most difficult burning condition is assumed. Heat losses due to radiation, refractory heat storage, and residue heat content are assumed to average 20 to 30 percent of the gross heating value of the refuse during the first hour of operation. Readily available furnace data indicate that the losses fall to approximately 10 to 15 percent of the gross heat after 4 to 5 hours of continuous operation.

The calculated overall average gas temperature should be about 1,000°F when calculations are based on 300 percent excess combustion air and the assumption of 20 to 30 percent heat loss given previously. This calculated temperature is not flame temperature and does not indicate the probable maximum temperatures attained in the flame port or mixing chamber. If the calculated temperature is lower than 1,000°F, installation of burners is indicated.

Only volume and temperature data for the products of combustion are required for determining the cross-sectional flow areas of the respective ports and chambers. The temperatures used are approximations of the actual temperature gradient in the incinerator as the products of combustion cool while passing through the various ports and chambers to the stack outlet.

Air ports are sized for admission of theoretical air plus 100 percent excess air. The remaining air enters the incinerator through the open charging door during batch operation and through expansion joints, cracks around doors, and so forth. Indraft velocities in the combustion air ports (overfire, underfire, and secondary) are assumed to be equal, with a velocity pressure of 0.1 inch water column (equivalent to 1,265 fpm). Designing the draft system so that available firebox draft is about 0.1 inch water column, and oversizing the adjustable airports ensure maintenance of proper air induction.

Calculations of draft characteristics follow standard stack design procedures common to all combustion engineering. The stack velocity given for natural draft systems accords with good practice and minimizes flow losses in the stack.

The remainder of the essential calculations needed for designing an incinerator are based upon substitution in the parametric equations and measurement of the incinerator. Recommended grate loading, grate area, and average arch height may be calculated by equation or estimated from Figures 310 and 311. Proper length-to-width ratios may be determined and compared with proposed values.

Supplementary computations are usually required in determining necessary auxiliary gas burner sizes and auxiliary fuel supply line piping. Where the moisture content of the refuse is less than 10 percent by weight, burners are usually not required. Moisture contents of from 10 to 20 percent normal-

Table 118. CHEMICAL PROPERTIES AND COMBUSTION DATA FOR PAPER, WOOD, AND GARBAGE

	Material	Sulfite paper,[a] %	Average wood,[b] %	Douglas fir,[c] %	Garbage,[d] %
Analysis	Carbon (C)	44.34	49.56	52.30	52.78
	Hydrogen (H)	6.27	6.11	6.30	6.27
	Nitrogen (N)		0.07	0.10	
	Oxygen (O)	48.39	43.83	40.50	39.95
	Ash	1.00	0.42	0.80	1.00
Gross Btu/lb Dry basis		7,590	8,517	9,050	8,820

Constituent (Based on 1 lb)		scf[e]	lb	scf	lb	scf	lb	scf	lb
Theoretical air		67.58	5.16	77.30	5.90	84.16	6.43	85.12	6.50
(40% sat at 60°F)		68.05	5.18	77.84	5.93	84.75	6.46	85.72	6.53
Flue gas with theoretical air	CO_2	13.99	1.62	15.64	1.81	16.51	1.91	16.66	1.93
	N_2	53.40	3.94	61.10	4.51	66.53	4.91	67.23	4.97
	H_2O formed	11.78	0.56	11.48	0.54	11.84	0.56	11.88	0.56
	H_2O (air)	0.47	0.02	0.53	0.02	0.58	0.02	0.59	0.02
Total		79.65	6.15	88.77	6.90	95.46	7.42	96.37	7.49
Flue gas with % excess air as indicated	0%	79.65	6.16	88.77	6.91	95.47	7.43	96.38	7.50
	50.0	113.44	8.74	127.42	9.86	137.55	10.64	139.24	10.77
	100.0	147.23	11.32	166.07	12.81	179.63	13.86	182.00	14.04
	150.0	181.26	13.91	204.99	15.78	222.01	17.09	224.86	17.21
	200.0	215.28	16.51	243.91	18.75	264.38	20.12	267.72	20.58
	300.0	283.33	21.70	321.75	24.68	349.13	26.58	353.44	27.12

[a] Constituents of sulfite paper, %

Cellulose	$C_6H_{10}O_5$	84
Hemicellulose	$C_5H_{10}O_5$	8
Lignin	$C_6H_{10}O_5$	6
Resin	$C_6H_{10}O_5$	2
Ash	$C_{20}H_{30}O_2$	1

[b] Kent, 1936.

[c] Kent, 1961.

[d] Estimated.

[e] Measured at 60°F and 14.7 psia.

ly necessitate installation of mixing chamber burners, and moisture contents of over 20 percent usually necessitate inclusion of ignition chamber burners.

General Construction

The design and construction of multiple-chamber incinerators are regulated in several ways. Ordinances and statutes that set forth basic building requirements have been established by most, if not all, municipalities. Air pollution control authorities have also set some limitations in material and construction that must be met, and manufacturers' associations have established recommended minimum standards to be followed.

The building codes governing incinerator construction adopted in the past have been based primarily upon concepts of structural safety and fire prevention by restriction of the rate of heat transfer through the walls. Little or no attention was given to the abrasion, erosion, spalling, and slagging that are encountered in a high-temperature incinerator, and yet these conditions lead to equipment failures that are comparable to structural or insulation failures.

The structural features and materials used in the construction of multiple-chamber incinerators can be discussed only in general terms. There are as many methods of erecting the walls of a multiple-chamber incinerator as there are materials from which to build them. Designs of multiple-chamber incinerators are presented schematically in Figures 312 and 313. The types of construction and fabrication shown are typical of those in current usage. The designs are shown with prefired refractory brick linings and common brick exterior walls. Structural details are not indicated since the reinforcing and support of walls, arches, and stack depend largely upon the size and type of construction of the unit under construction. While conventional "60° sprung arches" are shown for the main arches and curtain wall port openings, flat suspended arches and other standard types of sprung arches may be substituted satisfactorily. Air inlets have been shown both as circular and as rectangular ports. Either may be used to provide adequate inlet areas. The exterior of the incinerator may be of either brick or steel plate construction, and the refractory lining may be of firebrick, castable refractory, or plastic firebrick, or combinations thereof.

In accordance with standard practices, the exterior walls are protected further from extreme temperature conditions by providing a suitable peripheral airspace in brick construction, by providing air-cooling lanes, or by using insulation in units fabricated from steel.

Changes in the methods of construction of multiple-chamber incinerators are typified in the portable prefabricated units available today. Installation of incinerators such as these is reduced simply to placement of the unit on its foundation and attachment of an auxiliary fuel supply where needed, though transportation considerations of weight and size limit their capacity to 500 pounds or less per hour. Plastic and castable refractory linings in steel exteriors are used widely for this type of fabrication. All larger incinerators, regardless of the type of construction, and those incinerators for which brick is desired for an exterior are erected on the site.

Refractories

The most important element in construction of multiple-chamber incinerators, other than the design, is the proper installation and use of refractories. High-quality materials are absolutely necessary if a reasonable and satisfactory service life is to be expected. Manufacturers must use suitable materials of construction and be experienced in high-temperature furnace fabrication and refractory installation, since faulty construction may well offset the benefits of good design. In the choice of one of the many available materials, maximum service conditions should dictate the type of lining for any furnace. Minimum specifications of materials in normal refuse service should include high-heat-duty firebrick or 120 pounds per cubic foot castable refractory. These materials, when properly installed, have proved capable of resisting the abrasion, spalling, slagging, and erosion resulting from high-temperature incineration.

As the incinerator's capacity and severity of duty increase, superior refractory materials such as super duty firebrick and plastic firebrick should be employed. A recent improvement in standard construction has been the lining of all stacks with 2,000°F refractory of 2-inch minimum thickness.

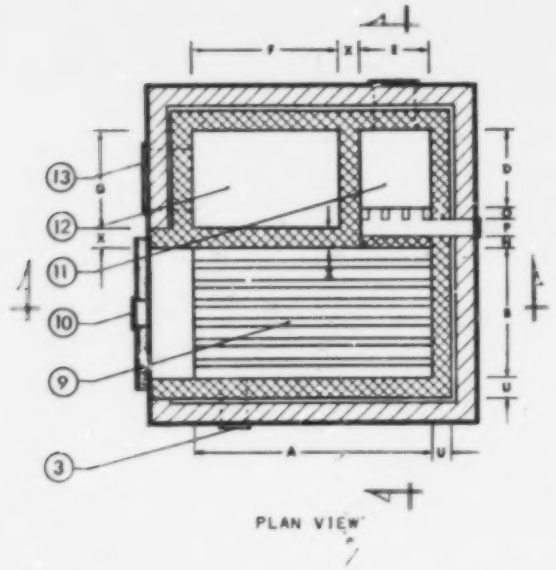
Grates and Hearths

The grates commonly used in multiple-chamber incinerators are made of cast iron in "Tee" or channel cross section. As the size of the incinerator increases, the length of the ignition chamber also increases. In the larger hand-charged incinerators, keeping the rear section of the grates completely covered is difficult because of the greater length of the ignition chamber. The substitution of a hearth at the rear of the ignition chamber in these units has been accepted as good practice, since a hearth in this region prevents open areas from being formed in the normally thin refuse pile. This prevents excessive underfire air from entering in front of the bridge wall, which would increase fly ash carryover and reduce combustion efficiency. Since surface combustion is the primary combustion principle, the use of a hearth has little effect upon combustion rate.

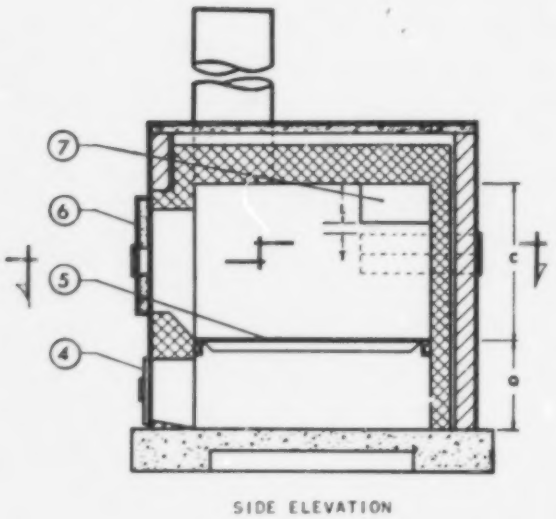
Installation of a sloping grate, which slants down from the front to the rear of the ignition chamber, facilitates charging. A grate such as this also increases the distance from the arch to the grates at the rear of the chamber and reduces the possibility of fly ash entrainment, which frequently occurs when the fuel bed surface approaches the level of the flame port.

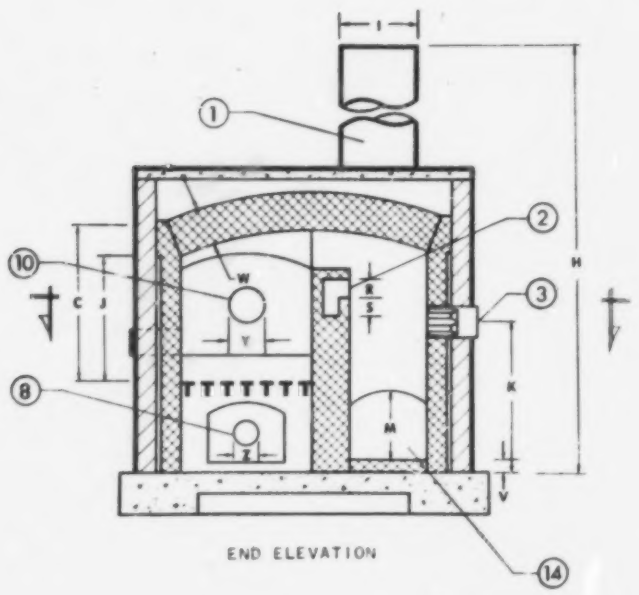
Air Inlets

Positive control for all combustion air inlets should be provided by means of fully adjustable dampers. The retort incinerator designs shown in Figure 312 incorporate round, spinner-type controls with rotating shutters for both underfire and overfire air openings, and rectangular ports with sliding or hinged dampers for the secondary air openings. The in-line incinerator designs shown in Figure 313 have rectangular ports for both overfire and secondary air openings, and spinner-style ports for the underfire air openings. Air ports may be of any convenient shape, though the port arrangement indicated in the in-line designs with rectan-



1. STACK
2. SECONDARY AIR PORT
3. GAS BURNERS
4. ASH PIT CLEANOUT DOOR
5. GRATES
6. CHARGING DOOR
7. FLAME PORT
8. UNDERFIRE AIR PORT
9. IGNITION CHAMBER
10. OVERFIRE AIR PORT
11. MIXING CHAMBER
12. COMBUSTION CHAMBER
13. CLEANOUT DOOR
14. CURTAIN WALL PORT

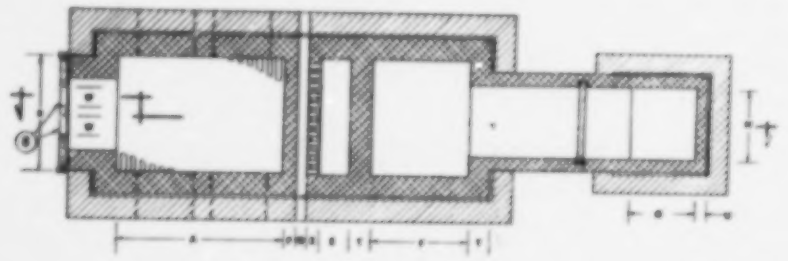




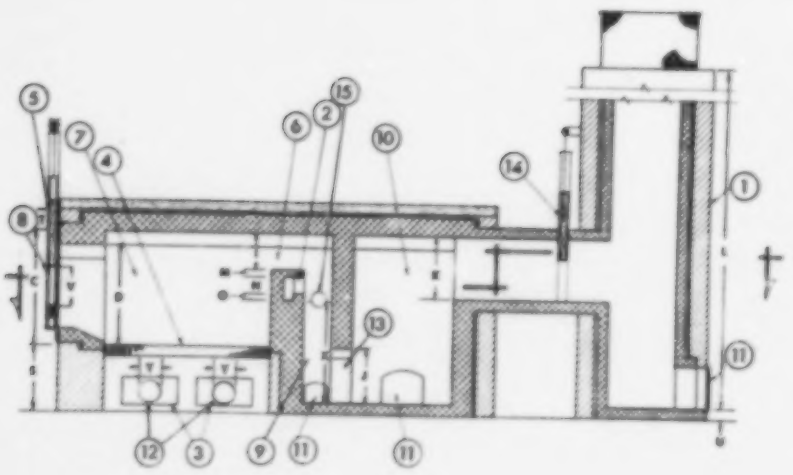
SIZE OF INCINERATOR, lb hr	LENGTH, inches																								
	A	B	C	D	E	F	G	H*	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Y	Z
50	31½	13½	22½	9	6½	20½	13½	18	8	18½	20	3½	10	4½	2½	2½	9	2½	2½	2½	4½	2½	4½	4½	6	4
100	40½	18	28½	13½	9	27	18	19	12	23	28	5	15	2½	2½	4	18½	5	0	2½	4½	2½	4½	4½	8	5
150	45	22½	33½	15½	11½	29	22½	20	14	27	35½	5	16½	4½	2½	4½	18	5	2½	2½	4½	2½	4½	4½	9	6
250	54	27	37½	18	13½	36	27	22	18	30	40	7½	18	4½	4½	4½	20	5	2½	2½	4½	2½	4½	4½	12	6
500	76½	36	47½	27	18	49½	36	28	24	36½	46½	12½	23	9	4½	4½	26	5	5	2½	9	4½	9	9	16	8
750	85½	49½	58	36	22½	58	45	32	30	40	51½	15	28	9	4½	4½	25	5	10	2½	9	4½	9	9	18	8
1000	94½	58	59½	36	27	58½	45	35	34	45	58½	17½	30	9	4½	4½	27½	7½	12½	2½	9	4½	9	9	22	10

*Dimension "H" given in feet.

Figure 312. Design standards for multiple-chamber, retort incinerators.



PLAN VIEW



SIDE ELEVATION

1. STACK
2. SECONDARY AIR PORTS
3. ASH PIT CLEANOUT DOORS
4. GRATES
5. CHARGING DOOR
6. FLAME PORT
7. IGNITION CHAMBER
8. OVERFIRE AIR PORTS
9. MIXING CHAMBER
10. COMBUSTION CHAMBER
11. CLEANOUT DOORS
12. UNDERFIRE AIR PORTS
13. CURTAIN WALL PORT
14. DAMPER
15. GAS BURNERS

SIZE OF INCINERATOR, lb/hr	LENGTH, inches																								
	A	B	C	D	E	F	G	H	I	J	K	L*	M	N	O	P	Q	R	S	T	U	V	W	X	Y
750	85½	49½	51½	45	15½	54	27	27	9½	24	18	32	4½	5	7½	9	2½	2½	30	9	4½	5	11	51	7
1000	98½	58	58	47½	18	63	31½	31½	11	29	22½	35	4½	5	10	9	2½	2½	30	9	4½	7	12	52	8
1500	99	76½	65	55	18	72	36	36	12½	32	27	38	4½	5	7½	9	4½	4½	30	9	4½	8	14	61½	9
2000	108	90	69½	57½	22½	79½	40½	40½	15	36	31½	40	4½	5	10	9	4½	4½	30	9	4½	9	15	65½	10

*Dimension "L" given in feet.

Figure 313. Design standards for multiple-chamber, in-line incinerators.

gular overfire ports is preferred since the combustion air is distributed more evenly across the fuel bed.

Stack

Stacks for incinerators with a capacity of 500 pounds or less per hour are usually constructed of a steel shell lined with refractory and mounted over the combustion chamber. A refractory-lined reinforced, red brick stack is an alternative method of construction when appearance is deemed important. Stacks for incinerators with a capacity of more than 500 pounds per hour are normally constructed in the same manner as those for smaller units but are often free standing for structural stability, as indicated in Figure 313. Stack linings should be increased in thickness as the incinerator becomes larger in size.

Induced-Draft System

The replacement of a stack by an induced-draft system introduces additional problems. Cooling the effluent gases becomes necessary to reduce their temperature to that for which the draft fan is rated. Evaporative cooling with water is a standard practice. The contact of the flue gas with water forms a weak acid solution that eventually corrodes the evaporative cooler and accessory equipment, making replacement necessary. To overcome these problems, stainless steel or acid-resistant brick may be installed. The excess spray water also creates a problem, requiring a sewer outlet for its disposal or a recirculation system for its reuse. Recirculation of acidic water not only results in more rapid corrosion of the spray chamber and fan, but also subjects the pump, piping, and spray nozzles to corrosion. The use of an induced-draft system with a spray chamber accomplishes additional removal of large particulate matter and water-soluble gases.

Operation

The most important single aspect of operation of a multiple-chamber incinerator is the method of charging the refuse into the ignition chamber. A multiple-chamber incinerator must be charged properly at all times in order to reduce the formation of fly ash and maintain adequate flame coverage of the burning rubbish pile and the flame port. A recommended charging cycle starts with the placing of the initial charge of refuse in the incinerator. The ignition chamber should be filled to a depth approximately two-thirds to three-fourths of the distance between the grates and the arch before lightoff. After approximately half of the refuse has been burned, the remaining refuse should be carefully stoked and pushed as far as possible to the rear of the ignition chamber. New refuse should be charged over the front section of the grates, which have been emptied by the moving of the burning refuse. To prevent smothering the fire, no material should be charged on top of the burning refuse at the rear of the chamber. With this charging method, live flames cover the rear half of the chamber, fill the flame port, and provide nearly complete flame coverage in the mixing chamber. The fire propagates over the surface of the newly charged material, spreading evenly and minimizing the possibility of smoke emissions. Since the refuse pile need not be disturbed unduly, little or no fly ash is emitted.

Characteristic of the multiple-chamber incinerator is that control of air-polluting emissions is built in, if the incinerator is operated with reasonable care. The discharge of combustion contaminants is almost entirely a function of ignition chamber design and the actions of the operator. Control of smoke is attained by proper admission of combustion air and by use of secondary burners in cases of incineration of refuse with a low heating value or high moisture content. The use of secondary burners is required at times since the efficiency of the mixing chamber depends upon both luminous flame and adequate temperatures for vapor phase combustion. The need for supplementary burners may be determined readily by observing the nature of the flame travel and coverage at both the flame port and the curtain wall port.

The overfire and underfire air ports are usually half-open at lightoff and are opened gradually to a full open position as the incinerator reaches its rated burning capacity. If black smoke is emitted, the admission of more secondary air and reduction of the capacity of other air ports are advisible. On the other hand, white smoke is usually the result of a too cold furnace and may be eliminated by reducing or closing all air ports. After the final charge or refuse, the air ports are closed gradually so that during the burndown period the only air introduced into the furnace is provided through leaks around door and port openings.

When ignition and mixing chamber burners are necessary, the mixing chamber or secondary burner is lighted before the incinerator is placed into operation. The burner should remain in operation for the first 15 to 20 minutes of operation and should be used thereafter as needed. Under normal conditions, the ignition chamber or primary burner is used only when wet refuse is charged. At other times, its use, too, may be required when refuse to be burned contains high percentages of inorganic compounds such as clay fillers used in quality paper.

Illustrative Problem

Problem:

Design a multiple-chamber incinerator to burn paper with 15 percent moisture at a rate of 100 lb/hr.

Solution:

1. Composition of refuse:

Dry combustibles	(100 lb/hr)(0.85)	= 85 lb/hr
Moisture	(100 lb/hr)(0.15)	= 15 lb/hr

2. Gross heat of combustion:

   From Table 118, the gross heating value of dry paper is 7,590 Btu/lb.

   (85 lb/hr)(7,590 Btu/lb) = 645,200 Btu/hr

3. Heat losses:

From Table 118, 0.56 lb of water is formed from the combustion of 1 pound of dry paper.

Radiation, etc = (0.20)(645,200 Btu/hr) = 129,040 Btu/hr

Evaporation of contained moisture (15 lb/hr)(1,060 Btu/lb) = 15,900 Btu/hr

Evaporation of water from combustion (0.56 lb/lb)(85 lb/hr)(1,060 Btu/lb) = 50,400 Btu/nr

Total = 195,340 Btu/hr

4. Net heat:

645,200 Btu/hr - 195,340 Btu/hr = 449,860 Btu/hr

5. Weight of products of combustion with 300 percent excess air:

From Table 118, 21.7 pounds of products of combustion result from the combustion of 1 pound of paper with 300 percent excess air.

Paper (85 lb/hr)(21.7 lb/lb) = 1,844 lb/hr
Water 15 lb/hr = 15 lb/hr

Total 1,859 lb/hr

6. Average gas temperature:

The specific heat of the products of combustion is 0.26 Btu/lb-°F.

$$\Delta t = \frac{449,860 \text{ Btu/hr}}{(0.26 \text{ Btu/lb-°F})(1,859 \text{ lb/hr})} = 930°F$$

$$T = 930°F + 60°F = 990°F$$

7. Combustion air requirements:

Basis:

Use 300 percent excess air; 200 percent excess air is admitted through open charging door and leakage around doors, ports, expansion joints, etc.

From Table 118, 68.05 cf of air is theoretically necessary to burn 1 pound of dry paper.

(85 lb/hr)(68.05 cf/lb)(2) = 11,580 cfh
or 192.8 cfm
or 3.2 cfs

8. Air port opening requirements at 0.1 in. WC:

From Table D8 in Appendix D, 1,255 fpm is equivalent to a velocity pressure of 0.1 inch.

$$\text{Total} = \frac{(192.8 \text{ cfm})(144 \text{ in.}^2/\text{ft}^2)}{1,255 \text{ ft/min}} = 22.2 \text{ in.}^2$$

Overfire airport (0.7)(22.2 $in.^2$) = 15.6 $in.^2$
Underfire airport (0.1)(22.2 $in.^2$) = 2.2 $in.^2$
Secondary airport (0.2)(22.2 $in.^2$) = 4.4 $in.^2$

9. Volume of products of combustion:

From Table 118, 283.33 cf of products of combustion are formed from the combustion of 1 pound of paper with 300 percent excess air.

Basis:

60°F and 300 percent excess air

Paper (85 lb/hr)(283.33 cf/lb) = 24,080 cfh

$$\text{Water } (15 \text{ lb/hr}) \frac{379 \text{ ft}^3/\text{lb-mol}}{18 \text{ lb/mol}} = 316 \text{ cfh}$$

Total 24,396 cfh
or 6.8 cfs

10. Volume of products of combustion through flame port:

Total volume minus secondary air
6.8 cfs - (3.2 cfs)(0.20) = 6.16 cfs

11. Flame port area:

From Table 116, velocity is 55 fps.

$$\frac{(6.16 \text{ cfs})(1,560°R)}{(55 \text{ fps})(520°R)} = 0.34 \text{ ft}^2$$

12. Mixing chamber area:

From Table 116, velocity is 25 fps.

$$\frac{(6.8 \text{ cfs})(1,460°R)}{(25 \text{ fps})(520°R)} = 0.76 \text{ ft}^2$$

13. Curtain wall port area:

From Table 116, velocity is 20 fps.

$$\frac{(6.8 \text{ cfs})(1,410°R)}{(20 \text{ fps})(520°R)} = 0.92 \text{ ft}^2$$

14. Combustion chamber area:

From Table 116, velocity is 6 to 10 fps.

$$\frac{(6.8\ \text{cfs})(1,360°\text{R})}{(6\ \text{fps})(520°\text{R})} = 2.96\ \text{ft}^2$$

15. Stack area:

From Table 116, velocity is < 30 fps.

$$\frac{(6.8\ \text{cfs})(1,360°\text{R})}{(25\ \text{fps})(520°\text{R})} = 0.71\ \text{ft}^2$$

16. Grate area:

From Figure 310, the grate loading for average refuse is 18 $\text{lb/ft}^2\text{-hr}$.

$$\frac{(100\ \text{lb/hr})}{18\ \text{lb/ft}^2\text{-hr}} = 5.56\ \text{ft}^2$$

17. Arch height:

From Figure 311, the arch height = 27 in.

18. Stack height:

From Table 116, $D_t \cong 0.17$ in. WC.

$$D_t = 0.52\,PH\left(\frac{1}{T} - \frac{1}{T_1}\right)*$$

where:

D_t = draft, in. WC
P = barometric pressure, psi
H = height of stack above grates, ft
T = ambient temperature, °Rankine
T_1 = average stack temperature, °Rankine.

$$H = \frac{D_t}{(0.52)(P)\left(\frac{1}{T} - \frac{1}{T_1}\right)}$$

$$H = \frac{0.17}{(0.52)(14.7)\left(\frac{1}{520} - \frac{1}{1,360}\right)} = 18.75\ \text{ft}$$

MOBILE MULTIPLE-CHAMBER INCINERATORS

Mobile multiple-chamber incinerators provide a unique method for on-the-site disposal of combustible refuse. Limited numbers of these units were constructed in Los Angeles County in the late 1950's and used successfully for land clearance, housing tract construction, and other industrial activities where the permanent installation of an incinerator or the hauling of refuse to another location for disposal would have been less economical. Although their technical efficiency was adequate, mobile multiple-chamber incinerators never achieved a popularity of any consequence because of availability of more economical disposal methods.

At first glance, one may presume that a standard multiple-chamber incinerator mounted on a trailer can serve as a mobile incinerator. This presumption is quickly dispelled when weight and size limitations, draft, vibration, and other problems inherent in mobile construction are more closely examined. The discussion that follows provides a designer with practical and economical answers that facilitate the design and construction of successful mobile multiple-chamber incinerators.

DESIGN PROCEDURE

Although mobile incinerators are designed with parameters identical to those of multiple-chamber incinerators, already described in this chapter, they must be constructed of lightweight materials and limited in size to compiy with the State Vehicle Code. Design configurations generally restrict the maximum capacity of the retort style, as shown in Figure 314, to 500 pounds per hour, and that of the in-line style, as shown in Figure 315, to 1,000 pounds per hour.

Draft for mobile incinerators may be produced in two ways. The first and most conventional way is the use of a stack, while the other incorporates an induced-draft system that uses air to cool the effluent.

Stack Requirements

If a stack is used, it must be retractable to meet the height requirements of the State Vehicle Code. To accomplish this, it is usually hinged at the base and, if necessary, folds in the middle, permitting it to lie horizontally on the top of the incinerator. The stack is unlined to reduce not only its weight but the size and weight of the elevating equipment, which consists of a frame, steel cables, and pulleys, operated by a hand crank or geared to a small gasoline engine.

Induced-Draft Fan System

A typical induced-draft system consists of an uninsulated breeching of 10-gage steel plate where products of combustion from the incinerator are cooled by mixing with air to a temperature that can be safely handled by an induced-draft fan. Cooling air is introduced through manually adjustable and barometric dampers located in the breeching.

*Kent, 1938.

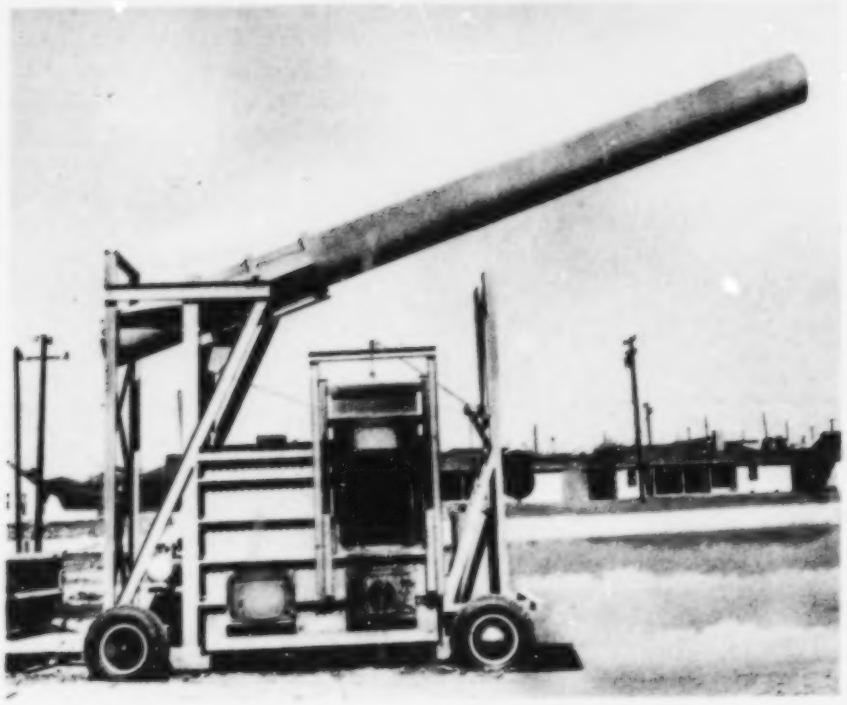


Figure 314. A 500-pound-per-hour mobile incinerator with retractable stack.

Figure 315. A 1,000-pound-per-hour mobile incinerator with retractable stack.

Heat and material balances, necessary for designing the breeching, are computed by the methods shown in the illustrative problem on page 431. The breeching should be sized to give an average velocity through its cross-sectional area of about 40 fps. At this velocity, adequate mixing of cooling air with the products of combustion occurs within 0.4 second, producing a relatively uniform temperature without excessive frictional losses. Designing the breeching for low frictional losses permits use of inexpensive axial-flow or propeller-type fans.

Manually adjustable dampers allow for introduction of dilution air into the breeching to cool the products of combustion. These dampers must be sized to provide sufficient air at the maximum burning rate of the incinerator to cool the gases to the design temperature of the fan. Barometric dampers balance the induced-draft system by sustaining an adequate and uniform draft in the incinerator. Their use comes into play primarily at lightoff and burndown when the charging door is closed and the airports are partially opened, restricting the gas flow through the incinerator. Under these conditions, the barometric dampers open more widely, allowing additional air to be induced into the breeching. This prevents an increased draft from developing in the ignition chamber. During capacity operation, when the gas flow through the incinerator is maximum, the balancing effect of barometric dampers is not required.

A major problem in the design of the induced-draft fan system is the proper selection of the fan. Fans capable of operating from ambient temperatures to temperatures in excess of 1,200°F are available. Fans designed to operate in excess of 800°F must be constructed of stainless steel and should be equipped with water-cooled bearings. These fans are costly; their bearing-cooling requirements virtually eliminate them from use on portable equipment.

Low-temperature fans with mild steel blades are capable of operating up to 300°F. The maximum operating temperature of these fans can be increased to 800°F by the addition of simple and inexpensive bearing coolers commonly called heat slingers. As the temperature increases above 300°F, the maximum permissible rpm is reduced for any class or duty of a specific fan. This capacity reduction ranges from about 10 percent at 600°F to 30 percent at 800°F. Therefore, it is necessary to install a larger fan of the same class or the same size fan of higher class when operating temperatures exceed 600°F.

If dilution air is introduced in excess of that necessary to cool the effluent to a temperature that can be handled by an inexpensive fan, this excess air will require an increase, not only in fan size, but also in horsepower and operating cost. All factors considered, the apparently optimum operating temperature of the fan is 600°F. At this temperature

an inexpensive and minimum sized fan constructed of mild steel can be used. Since propeller-type fans have the advantages of compactness, low cost, and light weight, they are usually selected over centrifugal types. Bronze blades available at a nominal increase in cost over steel blades and capable of operation up to 800°F are usually installed to provide a safety factor.

The induced-draft fan is powered by a small gasoline engine through a chain or belt drive. The engine is sized for maximum power requirements, which occur at lightoff when the air handled by the fan is at ambient temperature. As the temperature of the exhaust gases rises, the fan horsepower at a constant rpm decreases in proportion to the change in density of the gases. The draft of the incinerator can also be regulated by changing the speed of the gasoline engine driving the fan.

STANDARDS OF CONSTRUCTION

The mechanical design and construction of a mobile incinerator must not only meet the dimensional and weight requirements of the Vehicle Code but also provide a rigid frame and refractories of sufficient quality to provide a satisfactory service life.

Refractories

Since refractories constitute 60 to 75 percent of the total weight of a mobile incinerator, low-density refractory materials must be selected. These materials should have a minimum pyrometric cone equivalent (PCE) of 15 and be relatively resistant to abrasion, spalling, and physical shock. Thermal conductivity should be about 5.4 at 2,000°F by ASTM C-201 so that backing with insulation will not be necessary.

Because shaped firebricks are not suitable for mobile installations because of excessive weight and problems in anchoring firmly to walls, other refractories must be investigated. A number of standard castable refractories manufactured today meet these specifications. They are composed of approximately equal portions of alumina and silica, are easy to cast, and have a density of about 80 pounds per cubic foot.

Exterior walls and arches are secured against thin corrugated steel sheets with stainless steel anchors arranged on 12- to 15-inch centers, while interior walls are self-supporting. Walls and arches are usually 4-1/2 inches thick for incinerators with capacities of less than 600 pounds per hour and 6 inches thick for units of larger capacity. It is of the utmost importance that castable refractories be installed strictly in accord with the information and directions provided by the manufacturer.

The bridge wall is susceptible to damage by careless operation, and the curtain wall is subjected to high-temperature flame impingement accompanied by high velocities, which tend to erode its surface. At these locations, the use of heavier castable refractories, which are more resistant to abrasion and erosion, is advantageous. A number of materials with densities of about 120 pounds per cubic foot have the special qualities to fill this need.

Grates

Cast iron grates, available today in many sizes, shapes, and patterns, are satisfactory for burning general refuse, as described previously in this chapter. Castable refractory grates, described later in this chapter, should be installed in incinerators designed to burn large quantities of wood.

Air Inlets

Combustion air may be controlled by providing adjustable dampers in the throats of all air ports. Dampers used for controlling overfire and underfire air are subject to warpage from high temperatures and should be constructed of stainless steel or cast iron. The secondary air port damper is not subjected to much heat and may be constructed of 10-gage mild steel plate.

Structure

The trailer and frame for supporting the incinerator should be designed by qualified structural engineers. A trailer of welded steel construction must be rigid enough to prevent the transmission of stresses and strains to the refractory walls during travel over rough terrain. The external frame should also be engineered to cope not only with mechanical stresses imposed during transportation but also with thermal stresses produced during the operation of the incinerator.

Auxiliary Burners

Mobile incinerators usually burn refuse varying widely in composition, requiring auxiliary burners sized in accordance with the information presented in Table 116. These burners are fired with LPG supplied from tanks mounted upon the incinerator trailer.

STACK EMISSIONS

The quality and composition of emissions from mobile multiple-chamber incinerators are similar to those from stationary multiple-chamber incinerators in burning general refuse. The air pollutants in pounds per ton of refuse burned are given in Table 117.

Illustrative Problem

Problem:

Design an induced-draft fan system for a mobile multiple-chamber incinerator.

Given:

Refuse to be burned is 1,000 pounds of wood per hour with 20 percent by weight moisture.

Solution:

1. Weight of products of combustion with 300 percent excess air:

   From Table 118, there are 24.68 lb of combustion products from the combustion of 1 lb of average dry wood with 300 percent excess air, 40 percent saturated.

Wood	(800 lb/hr)(24.68 lb/lb) =	19,750 lb/hr
Moisture		200 lb/hr
Total		19,950 lb/hr

2. Weight of dilution air required to reduce products of combustion from 900° to 600°F:

   Assume combustion products are equivalent to air in composition. Average specific heat of air is 0.26 Btu/lb-°F.

$$(w_a)(c_{p2})(t_2 - t_a) = (w_{pc})(c_{p1})(t_1 - t_2)$$

where:

w_a = weight of dilution air, lb/hr

w_{pc} = weight of combustion products; lb/hr

c_{p1} = average specific heat of products of combustion, Btu/lb-°F

c_{p2} = average specific heat of air, Btu/lb-°F

t_2 = final temperature, °F

t_1 = initial temperature of combustion products, °F

t_a = air temperature, °F

$$w_a = \frac{(19,950 \text{ lb/hr})(0.26 \text{ Btu/lb-°F})(900°F - 600°F)}{(0.26 \text{ Btu/lb-°F})(600°F - 60°F)}$$

$$= 11,100 \text{ lb/hr}$$

3. Flow of dilution air at 60°F:

$$(11,100 \text{ lb/hr})\left(\frac{379 \text{ ft}^3/\text{lb mole}}{29 \text{ lb/lb mole}}\right)\left(\frac{1 \text{ hr}}{60 \text{ min}}\right)$$

$$= 2,420 \text{ cfm or } 40.3 \text{ cfs}$$

4. Gas flow through breeching:

   From Table 118, there are 321.7 ft^3 of combustion products at 60°F from combustion of 1 lb of average dry wood with 300 percent excess air.

Wood	(800 lb/hr)(321.7 ft^3/lb) =	257,000 cfh
Moisture	(200 lb/hr)$\left(\frac{379 \text{ ft}^3/\text{lb mole}}{18 \text{ lb/lb mole}}\right)$	4,200 cfh
Total		261,200 cfh

   Dilution air at 60°F $(2,420 \text{ cfm})\left(\frac{60 \text{ min}}{1 \text{ hr}}\right)$

Total	=	145,000 cfh
		406,200 cfh
	or	6,770 cfm
	or	113 cfs

   Total gas flow at 600°F

$$\frac{(1,060°R)}{(520°R)}(6,770 \text{ cfm}) = 13,000 \text{ cfm}$$

or 230 cfs

5. Cross section of breeching:

   Design breeching for an average gas flow rate of 40 fps at 600°F:

$$\text{Area} = \frac{(230 \text{ cfs})}{(40 \text{ fps})} = 5.75 \text{ ft}^2$$

   Dimensions: 18 in. high x 46 in. wide.

6. Length of breeching:

   Design breeching for a residence time of 0.45 sec at 40 fps

   Length = (0.45 sec)(40 fps) = 18 ft

   Use a double-pass breeching 9 ft long to fit on top of the incinerator.

7. Static pressure behind adjustable dampers and barometric dampers at capacity operation:

   Assume static pressure behind the adjustable dampers and barometric dampers is essentially the same.

(a) Assume static pressure in combustion chamber, SP = 0.30 in. WC

(b) Contraction loss from combustion chamber into duct leading to breeching:

$$\text{Ratio } r = \frac{\text{cross-sectional area of duct}}{\text{horizontal cross-sectional area combustion chamber}}$$

$$r = \frac{5.75 \text{ ft}^2}{17.5 \text{ ft}^2} = 0.33$$

Contraction loss is 0.38 VP* (velocity pressure head) at the velocity through the duct.

Velocity through 5.75 ft^2 port at 900°F

$$\frac{(261,200 \text{ cfh})}{(3,600 \text{ scfs/hr})} \frac{(1,360°\text{R})}{(520°\text{R}} \frac{(1)}{(5.75 \text{ ft}^2} = 32.9 \text{ fps}$$

Assume composition of combustion products is equivalent to air.

Velocity head of 32.9 fps at 900°F

$$v = 2.9\sqrt{t\,h}\ \dagger$$

where:

v = gas velocity, fps

t = absolute gas temperature, °R

h = velocity pressure (head), in. WC

$$h = \left(\frac{v}{2.9}\right)^2 \frac{(1)}{(t)}$$

$$h = \left(\frac{32.9 \text{ fps}}{2.9}\right)^2 \left(\frac{1}{1,360°\text{R}}\right)$$

h = 0.090 in. WC

Contraction loss

$$(0.38 \text{ VP}) \frac{(0.090 \text{ in. WC})}{1 \text{ VP}} = 0.04 \text{ in. WC}$$

*Badger and McCase, 1936.

†Research-Cottrell, Inc.

(c) Right-angle bend into breeching.

Assume 1 VP loss for right-angle bend.

1 VP at 32.9 fps and 900°F = 0.09 in. WC

(d) Total static pressure

a + b + c = total static pressure

(0.30 in. WC) + (0.04 in. WC) + (0.09 in. WC) = 0.43 in. WC

8. Indraft velocity through dampers:

Design breeching for a gas velocity of 40 fps at 600 F. At a velocity pressure of 40 fps and 600°F,

$$h = \left(\frac{v}{2.9}\right)^2 \frac{(1)}{(t)}$$

$$h = \left(\frac{40 \text{ fps}}{2.9}\right)^2 \left(\frac{1}{1,060°\text{R}}\right) = 0.18 \text{ in. WC}$$

Total pressure = velocity pressure + static pressure.

Total pressure = 0.18 in. WC + 0.43 in. WC = 0.61 in. WC.

Assume static friction loss through dampers is 0.65 VP.

Total pressure = velocity pressure + static pressure.

0.61 in. WC = 1 VP + 0.65 VP

VP = 0.37 in. WC

From Table D8, Appendix D, the velocity at 60°F and 0.37 in. WC is 2,410 fpm.

9. Size of adjustable dampers (assume barometric dampers closed):

Design dampers 100% oversize to allow for operation of the incinerator in excess of design capacity.

Dilution air = 2,420 cfm

$$\frac{(2,420 \text{ cfm})}{(2,410 \text{ fpm})} (2) = 2.03 \text{ ft}^2$$

10. Static-pressure drop through induced-draft system at capacity operation with a 600°F outlet temperature:

(a) Static pressure at dampers, SP = 0.43 in. WC

(b) Double pass breeching 18 feet long:

$$f = \frac{0.002\, hv^{2*}}{mt}$$

where:

f = friction, in. WC

h = duct length, ft

v = gas velocity, fps

t = absolute gas temperature, °R

m = hydraulic radius

$$m = \frac{\text{cross-sectional area of breeching, ft}^2}{\text{perimeter of breeching, ft}}$$

$$f = \frac{(.002)(18)\ (40)^2}{(0.54)(1,060)} = 0.10 \text{ in. WC}$$

(c) 180° bend at one end of breeching.

Assume 2-VP loss at 40 fps and 600°F

$$h = \left(\frac{v}{2.9}\right)^2\left(\frac{1}{t}\right)$$

$$h = \left(\frac{40}{2.9}\right)^2\left(\frac{1}{1,060}\right) = 0.18 \text{ in. WC}$$

$$(2 \text{ VP})\frac{(0.18 \text{ in. WC})}{(1 \text{ VP})} = 0.36 \text{ in. WC}$$

(d) 90° bend at fan discharge.

Use 9 ft^2 opening to reduce pressure drop.

Assume 1-VP loss for 90° bend at 600°F.

$$\text{Velocity} = (40 \text{ fps})\frac{(5.75 \text{ ft}^2)}{(9 \text{ ft}^2)} = 25.6 \text{ fps}$$

$$h = \left(\frac{v}{2.9}\right)^2\left(\frac{1}{t}\right)$$

$$h = \left(\frac{25.6}{2.9}\right)^2\left(\frac{1}{1,060}\right) = 0.07 \text{ in. WC}$$

$$(1 \text{VP})\frac{(0.07 \text{ in. WC})}{(1 \text{ VP})} = 0.07 \text{ in. WC}$$

(e) Total static pressure for system:

(a) + (b) + (c) + (d) = total static pressure

(0.43) + (0.10) + (0.36) + (0.07) = 0.96 in. WC

*Griswold, 1946.

11. Calculate points on system static-pressure curve based upon capacity operation at 600°F:

$$sp_2 = (sp_1)\left(\frac{cfm_2}{cfm_1}\right)^2$$

where:

sp_2 = unknown static pressure

cfm_2 = proposed cfm

cfm_1 = known cfm

sp_1 = known static pressure

Assume cfm_2 = 10,000

$$sp_2 = (0.96)\left(\frac{10,000}{13,000}\right)^2 = 0.57 \text{ in. WC}$$

Assume cfm_2 = 20,000

$$sp_2 = (0.96)\left(\frac{20,000}{13,000}\right)^2 = 2.28 \text{ in. WC}$$

12. Fan specifications:

Select fan that will deliver, as near as possible, 13,000 cfm at 0.96 in. WC and 600°F.

Fan performance given for 60°F operation:

1,160 rpm 60°F

1.4 in. WC	2.0 in. WC	2.2 in. WC
21,000 cfm	13,800 cfm	10,000 cfm
10 bhp	7.5 bhp	6.7 bhp

Calculate points for 600°F fan performance curve: With rpm and cfm held constant, static pressure and bhp vary directly with gas density or inversely with absolute temperature.

$$\text{Ratio} = \frac{520°F}{1,060°F} = 0.49$$

1,160 rpm 600°F

0.7 in. WC	1.0 in. WC	1.1 in. WC
21,000 cfm	13,800 cfm	10,000 cfm
4.9 bhp	3.7 bhp	3.3 bhp

13. Operating point at 600°F:

Intersection of 600°F system curve with 600°F fan curve is shown in Figure 316.

13,400 cfm
1.02 in. WC at 600°F
1,160 rpm
3.7 bhp

14. Static-pressure drop for induced-draft system at 60°F:

This condition occurs at light-off before ignition. Assume negligible airflow through incinerator and static pressure 0.3 in. WC in combustion chamber and behind barometric and adjustable dampers.

Assume total airflow through fan is 13,000 cfm.

(a) Behind dampers static pressure = 0.30 in. WC.

(b) Friction through 18-foot-long breeching:

Cross-sectional area = 5.75 ft^2

$$f = \frac{0.002\ hv^2}{mt}$$

$$f = \frac{(0.002)(18)(40)^2}{(0.54)(520)} = 0.21 \text{ in. WC}$$

(c) 180° bend at end of breeching:

Assume 2-VP loss at 40 fps and 60°F

From Table D8, Appendix D, VP = 0.36 in. WC

$$(2\ VP)\ \frac{(0.36 \text{ in. WC})}{(1\ VP)} = 0.72 \text{ in. WC}$$

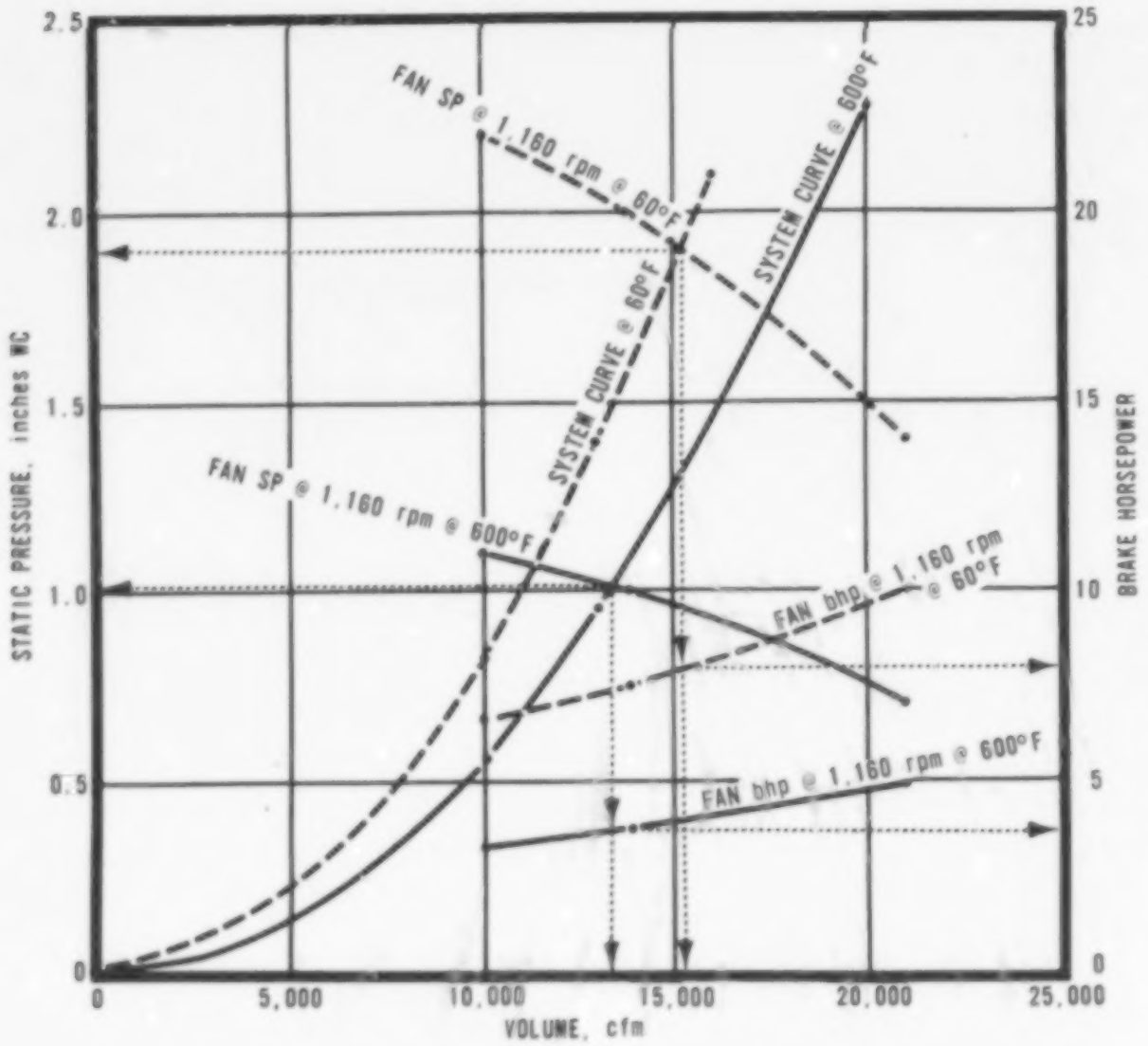


Figure 316. Fan and system curves at 60°F and 600°F.

(d) 90° bend fan discharge through 9 ft^2 outlet:

Assume 1 VP at 26.5 fps at 60°F

From Table D8, Appendix D, 1 VP = 0.16 in. WC

$$(1\ VP)\ \frac{(0.16\ in.\ WC)}{(1\ VP)} = 0.16\ in.\ WC$$

(e) Total static pressure:

a + b + c + d = 1.39 in. WC

15. System static-pressure curve development at 60°F:

$$sp_2 = (sp_1)\left(\frac{cfm_2}{cfm_1}\right)^2$$

Assume cfm_1 = 10,000

$$sp_2 = (1.39)\left(\frac{10,000}{13,000}\right)^2 = 0.82\ in.\ WC$$

Assume cfm_2 = 16,000

$$sp_2 = (1.39)\left(\frac{16,000}{13,000}\right)^2 = 2.10\ in.\ WC$$

16. Operating point at lightoff where the 60°F system curve intersects the 60°F fan curve (see Figure 316):

15,200 cfm
1.90 in. WC at 60°F
1,160 rpm
8.0 bhp

Select a 10-hp gasoline engine to drive the fan.

17. Total system pressure behind dampers:

Assume negligible airflow through incinerator at lightoff.

Static pressure behind adjustable and barometric dampers at 60°F:

$$sp_2 = (0.3)\left(\frac{15,200}{13,000}\right)^2 = 0.41\ in.\ WC$$

Total air velocity at 60°F in breeching:

$$\frac{15,200\ cfm}{5.75\ ft^2} = 2,640\ fpm$$

From Table D8, Appendix D, VP = 0.41 in. WC

Total pressure = velocity pressure + static pressure

Total pressure = 0.44 in. WC + 0.41 in. WC

Total pressure = 0.85 in. WC

18. Air velocity through adjustable and barometric dampers:

Assume friction loss through dampers at 0.65 VP inlet.

Total pressure = velocity pressure + static pressure

0.85 in. WC = 1 VP + 0.65 VP

VP = 0.52 in. WC

From Table D8, Appendix D, inlet velocity is 2,860 fpm.

19. Airflow through adjustable dampers:

$$(2.03\ ft^2)(2,860\ fpm) = 5,800\ cfm$$

20. Airflow through barometric dampers:

Assume negligible airflow through incinerator

Total airflow through fan	15,200 cfm
Adjustable dampers	5,800 cfm
Barometric dampers	9,400 cfm

21. Selection of barometric dampers:

Minimum damper area.

$$Area = \frac{(9,400\ cfm)}{(2,860\ fpm)} = 3.28\ ft^2$$

Select four 15-in.-diameter barometric dampers with total area about 40% in excess of minimum area to allow for operating flexibility.

Total open area of 4 dampers:

$$4\ dampers\ \frac{(1.23\ ft^2)}{(damper)} = 4.9\ ft^2$$

MULTIPLE-CHAMBER INCINERATORS FOR BURNING WOOD WASTE

INTRODUCTION

Although a small part of the wood waste produced from lumber mills and wood-working industries can be processed into useful products such as chip board, fireplace logs, and paper, the bulk of this waste is disposed of by incineration, open burning, or hauling to a dump. The most satisfactory air pollution solution is, of course, landfill disposal. The final choice of the method of disposal is primarily determined by economics and by the air pollution regulations existing in the locale.

There are, in general, three methods of burning wood waste. These are (1) open burning, that is, burning in a pile without any surrounding structure; (2) burning in single-chamber incinerators, including the tepee and silo structures; and (3) burning in multiple-chamber incinerators. Of these, the latter is the most satisfactory from an air pollution standpoint.

Open burning with no control over combustion air produces more air contaminants than single-chamber incinerators do with regulated air supply. The tepee and silo single-chamber incinerators also differ in combustion efficiency and emission of air contaminants.

Tepee incinerators are simple structures consisting usually of nothing more than a sheet metal shell supported by structural steel members in a shape similar to that of an Indian tepee. They are usually located at lumber mills and have limited control of primary combustion air. Many units employ blowers to supply air to the base of the burning pile to increase the burning rate. The metal shell is cooled by peripheral air, which flows upward and over the inside surfaces. Excessive combustion air admitted in this manner prevents good control of the combustion process and results in excessive smoke and other air contaminants.

A silo incinerator consists of a steel cylindrical chamber lined with high-duty refractory materials. The top of the cylindrical chamber usually tapers to a smaller diameter and extends upward, forming a stack to promote draft. Air is admitted through louvers located near the base of the structure. High temperatures can be maintained in the refractory-lined chamber, resulting in higher combustion efficiencies than in the tepee units. Single-chamber silo incinerators are not, however, satisfactory where air pollution is a serious problem, and have been found to emit particulate matter in excess of 12 pounds per ton of wood waste burned.

Description of the Refuse

Wood waste is produced by industry in a great many sizes and shapes ranging from fine sander dust to large pieces of lumber. Physical properties and combustion data for several common woods are given in Table 118. Green lumber at the mill varies widely in moisture content. For example, green redwood may contain over 50 percent moisture by weight, while construction-grade lumber such as Douglas fir contains from 10 to 25 percent moisture depending upon its age. Kiln-dried wood may contain as little as 5 or 6 percent moisture.

THE AIR POLLUTION PROBLEM

Burning of wood waste in open areas and at dump sites or in single-chamber incinerators is accompanied by dense clouds of smoke, fly ash, and disagreeable odors. Basically, these air contaminants are caused by incomplete combustion and are discharged in the form of particulate matter, aldehydes, hydrocarbons and organic acids, as well as smoke and fly ash. They are usually present in the greatest concentrations after the lightoff period or during times of heavy charging.

While single-chamber silo incinerators have been found to have particulate emissions in excess of 12 pounds per ton of wood waste, the particulate discharge from multiple-chamber incinerators designed to burn small wood particles ranges from 1-1/2 to 6-1/2 pounds per ton of wood waste burned, as shown in Table 119. Smoke is visible from a well-designed multiple-chamber incinerator only for a few minutes after lightoff and is occasionally accompanied by minute amounts of fly ash.

AIR POLLUTION CONTROL EQUIPMENT

Air pollution from the burning of wood waste can be reduced to a minimum through the use of multiple-chamber incinerators. By promoting complete combustion, multiple-chamber incinerators produce considerably less air pollution than is emitted from single-chamber incinerators or by open burning. Multiple-chamber incinerators discussed in the remainder of this part of the chapter are designed to burn all forms of wood waste--from large pieces of lumber to sawdust particles that may comprise from 10 to 100 percent of the total weight of the charge. The designs of mechanical feed systems are also included since the feed system must be properly integrated with the design of the incinerator to promote maximum combustion.

DESIGN PROCEDURE

The fundamental principles of combustion discussed in the first part of this chapter are applicable to designing these incinerators. Where 10 percent

Table 119. SOURCE TEST DATA FOR MULTIPLE-CHAMBER INCINERATORS BURNING WOOD

Item	Units	Test No.				
		1	2	3	4	5
Incinerator capacity	lb/hr	150	350	750	1,000	3,000
Normal burning rate	lb/hr[a]	170	300	740	1,055	2,910
Moisture content of refuse	wt %	10	5	10	25	10
Stack volume	scfm	420	557	3,260	3,300	15,300
Secondary chamber temperature	°F	1,600	1,400	1,500	1,850	1,600
Particulate matter	gr/scf at 12% CO_2	0.058	0.038	0.095	0.23	0.11
Particulate matter	lb/ton[b]	2.0	1.4	3.2	6.6	3.6
Sulfur dioxide	lb/ton[b]	0	0	0	0	0
Carbon monoxide	lb/ton[b]	0	0	0	0	0
Organic acid--as acetic	lb/ton[b]	0.8	1.2	0.54	0.85	1.2
Aldehydes--as formaldehyde	lb/ton[b]	2.0	1.9	0.8	3.0	6.0
Hydrocarbons--as hexane	ppm	9	9	9	9	9

[a]Burning rate based on stack analysis.
[b]Pounds of contaminants per ton of wood burned.

or more of the wood waste is in the form of sawdust and shavings, it must be fed at a continuous rate by a mechanical feed system. Differences in some design factors from those given at the beginning of this chapter for hand-charged general-refuse incinerators generally reflect the higher temperatures developed from the exclusive and continuous mechanical charging of wood, and differences in the distribution of combustion air.

The gross heating value of kiln-dried wood is 9,000 Btu per pound and is represented by the upper curves of Figures 310 and 311. These curves can be used to determine grate loading and average arch height, respectively. Other design factors differing from those for general-refuse incinerators are given in Table 120. These design factors include secondary chamber cross-sectional areas, inlet air port sizes, and other values and proportions.

An illustrative problem at the end of this part of the chapter shows how these factors are used to design a multiple-chamber incinerator with a mechanical feed system. The calculations in this problem fall into three general categories: (1) Combustion calculations based upon refuse composition, projected air requirements, and heat transfer; (2) gaseous flow calculations based upon the products of combustion at elevated temperatures; and (3) dimensional calculations based upon equations determined empirically from source testing.

Chemical properties and combustion data for average wood and Douglas fir, given in Table 118, and similar values for other kinds of wood can be used to determine the weights, velocities, and average temperatures of the products of combustion.

For calculation purposes, the burning rate and wood waste composition are assumed constant, and the incinerator is considered to be under relatively steady-state conditions. Calculations are always based upon refuse that is the most difficult to burn. Heat losses by radiation, heat stored in refractory, and heat content of the residue are assumed to average 20 to 30 percent of the gross heating value of the refuse during the first hour of operation. These heat losses drop to 10 to 15 percent after 4 or 5 hours of operation.

To determine the cross-sectional flow areas of the secondary ports and chambers, only volumes and temperature levels of the products of combustion are required. The temperature gradient in which the products of combustion cool as they pass from the flame port to the stack are averages based upon source tests of similar incinerators.

The calculated overall average gas temperature should be about 1,300°F based on 200 percent excess combustion air and the 20 to 30 percent heat losses. The calculated temperatures are not flame temperatures and do not indicate temperatures attained in the flame port or mixing chamber.

Indraft velocities through the ignition chamber air ports are assumed to average 900 fpm, equivalent to a velocity pressure of 0.05 inch WC, while indraft velocities through the secondary air ports av-

Table 120. DESIGN FACTORS FOR MULTIPLE-CHAMBER INCINERATORS FOR BURNING WOOD WASTE

Item and symbol	Recommended value and units	Allowable deviation
Primary combustion zone:		
Grate loading, L_G	10 Log R_c: lb/hr-ft^2 where R_c equals the refuse combustion rate in lb/hr (refer to Figure 310)	± 10%
Grate area, A_G	$R_c \div L_G$: ft^2	± 10%
Average arch height, H_A	4/3 $(A_G)^{4/11}$; ft (refer to Figure 311 and + 10% curve)	----
Length-to-width ratio (approx):		
Retort	Up to 500 lb/hr, 2:1; over 500 lb/hr, 1.75:1	----
In-line	Diminishing from about 1.7:1 for 750-lb/hr to about 1:2 for 2,000-lb/hr capacity. Oversqaure acceptable in units of more than 11-ft ignition chamber length	----
Secondary combustion zone:		
Gas velocities:		
Flame port at 1,900°F, V_{FP}	50 ft/sec	± 20%
Mixing chamber at 1,550°F, V_{MC}	25 ft/sec	± 20%
Curtain wall port at 1,500°F, V_{CWP}	20 ft/sec	± 20%
Combustion chamber at 1,200°F, V_{CC}	5 to 10 ft/sec; always less than 10 ft/sec	----
Mixing chamber downpass length, L_{MC}, from top of ignition chamber arch to top of curtain wall port	Average arch height, ft	± 20%
Length-to-width ratios of flow cross sections:		
Retort, mixing chamber, and combustion chamber	Range: 1.3:1 to 1.5:1	----
In-line	Fixed by gas velocities due to constant incinerator width	----
Combustion air:		
Air requirement, batch, or continuous charging	Basis: 200% excess air. 100% excess air admitted into ignition chamber; 50% theoretical air through mixing chamber air ports and 50% theoretical air through curtain wall air port or side air ports.	----
Combustion air distribution, % of total air required:		
Overfire air ports	60%	----
Underfire air ports	6%	----
Mixing chamber air ports	17%	----
Curtain wall port or side ports	17%	----
Port sizing, nominal inlet, velocity pressure, and velocity (without oversize factors), in. WC or fpm:		
Overfire port	0.051 or 900	
Underfire port	0.051 or 900	
Mixing chamber port	0.062 or 1,000	
Curtain wall port or side port	0.062 or 1,000	
Furnace temperature:		
Average temperature, combustion products at 200% excess air	1,300°F	± 20°F
Auxiliary burners:		
Secondary burner (if required)	2,500 to 5,000 Btu per lb of moisture in the refuse	
Draft requirements:		
Theoretical stack draft, D_T	0.15 to 0.35 in. WC	----
Available primary air induction draft, D_A (assume equivalent to inlet velocity pressure)	0.05 to 0.10 in. WC	
Natural draft stack velocity, V_g	Less than 25 ft/sec at 1,100°F	----

erage 1,000 fpm (0.06 in. WC). The incinerator draft system should be designed to produce a negative static pressure of at least 0.05 inch WC in the ignition chamber.

Primary air ports for continuously fed incinerators are sized for induction of theoretical plus 100 percent excess air. Ten percent of this air is admitted through ports located below the grates, and 90 percent, above the grates. Additional primary air can be admitted by opening the charging door when necessary. Air is induced into the mixing chamber not only to support combustion but also to cool the combustion gases and prolong the service life of the refractories. Mixing chamber air ports located in the bridge wall are sized to admit 50 to 100 percent of theoretical air. Air is sometimes admitted to the combustion chamber through air ports located in the curtain wall and sized to admit an additional 50 percent of theoretical air.

Although some combustion air enters the ignition chamber along with the sawdust from the pneumatic conveying system, this air usually amounts to less than 7 percent of the total combustion air and can be neglected in determining the size of the primary air ports. Air ports are designed with the factors given in Table 120.

Unless the wood refuse is extremely wet, auxiliary gas burners are not required in the ignition chamber to initiate and sustain combustion. If products such as rubber, oily rags, and plastics are present in appreciable quantities in the wood wastes, they produce partially oxidized compounds that require high temperatures for complete secondary combustion. Thus, secondary burners should be installed in the mixing chamber with automatic controls to maintain the required high temperatures under all phases of operation.

Incinerator Arrangements

Incinerators for burning wood use both in-line and retort styles as shown in Figures 317 and 318. Incinerators with capacities of less than 500 pounds per hour are usually constructed as retorts. Units ranging from 500 to 1,000 pounds per hour may, however, follow either the in-line or retort style for the arrangement of chambers. In-line styles are recommended for incinerators with capacities in excess of 1,000 pounds per hour because of not only the inherent higher costs of the retort but also the difficulties in cooling the internal walls. A retort-type incinerator with a prefabricated steel shell is shown in Figure 318. A single-chamber, silo-type incinerator can be converted to multiple chamber by attaching a dutch oven consisting of an ignition chamber and a mixing chamber as depicted in Figures 319 and 320.

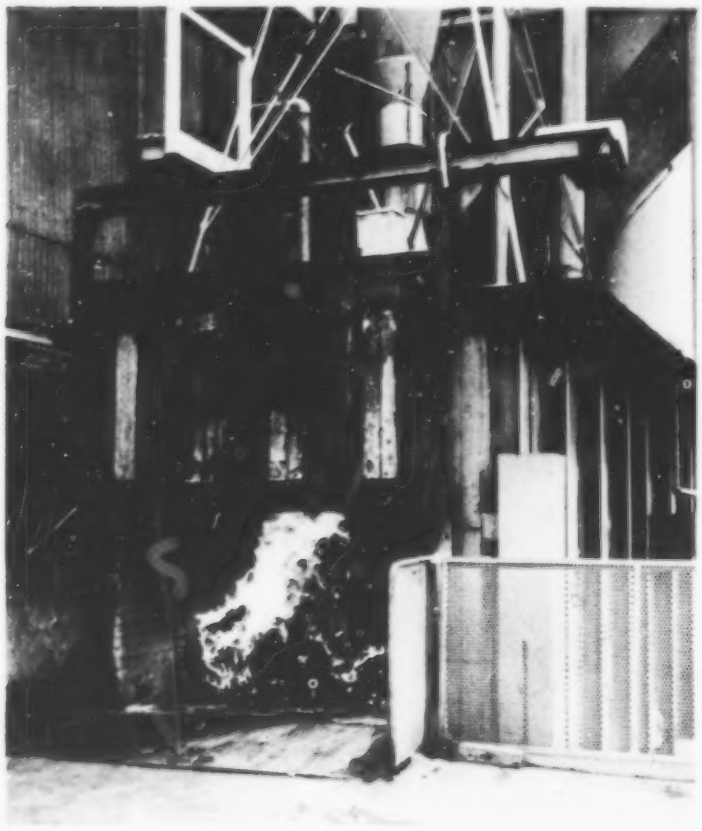


Figure 317. A 2,000-lb-per-hour, in-line multiple-chamber incinerator (Metro Goldwyn Mayer, Inc., Culver City, Calif.).

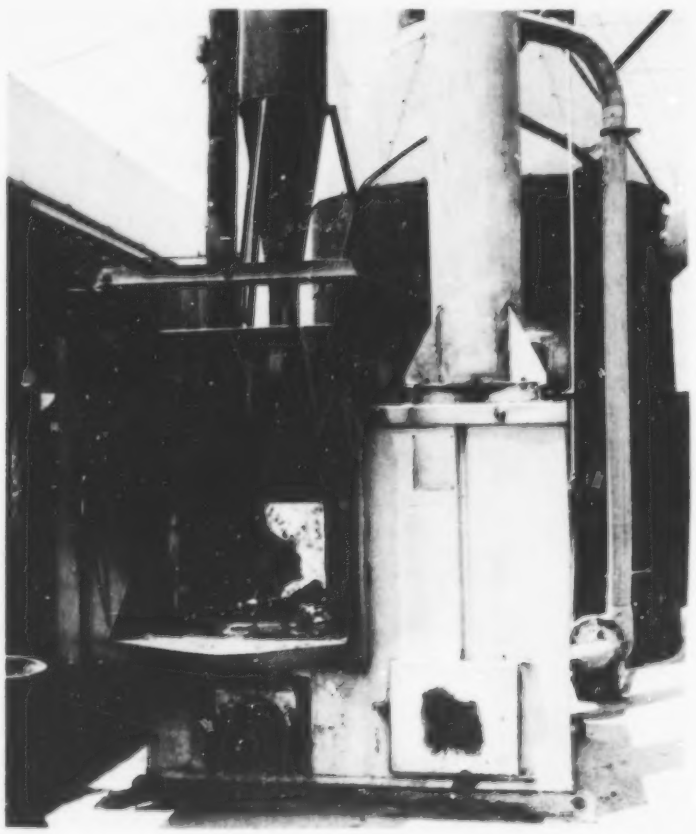


Figure 318. A 150-lb-per-hour, retort multiple-chamber incinerator (Acme Woodcraft, Los Angeles, Calif.).

Figure 319. A 1,000-lb-per-hour, in-line multiple-chamber incinerator (silo conversion) (Orban Lumber Co., Pasadena, Calif.).

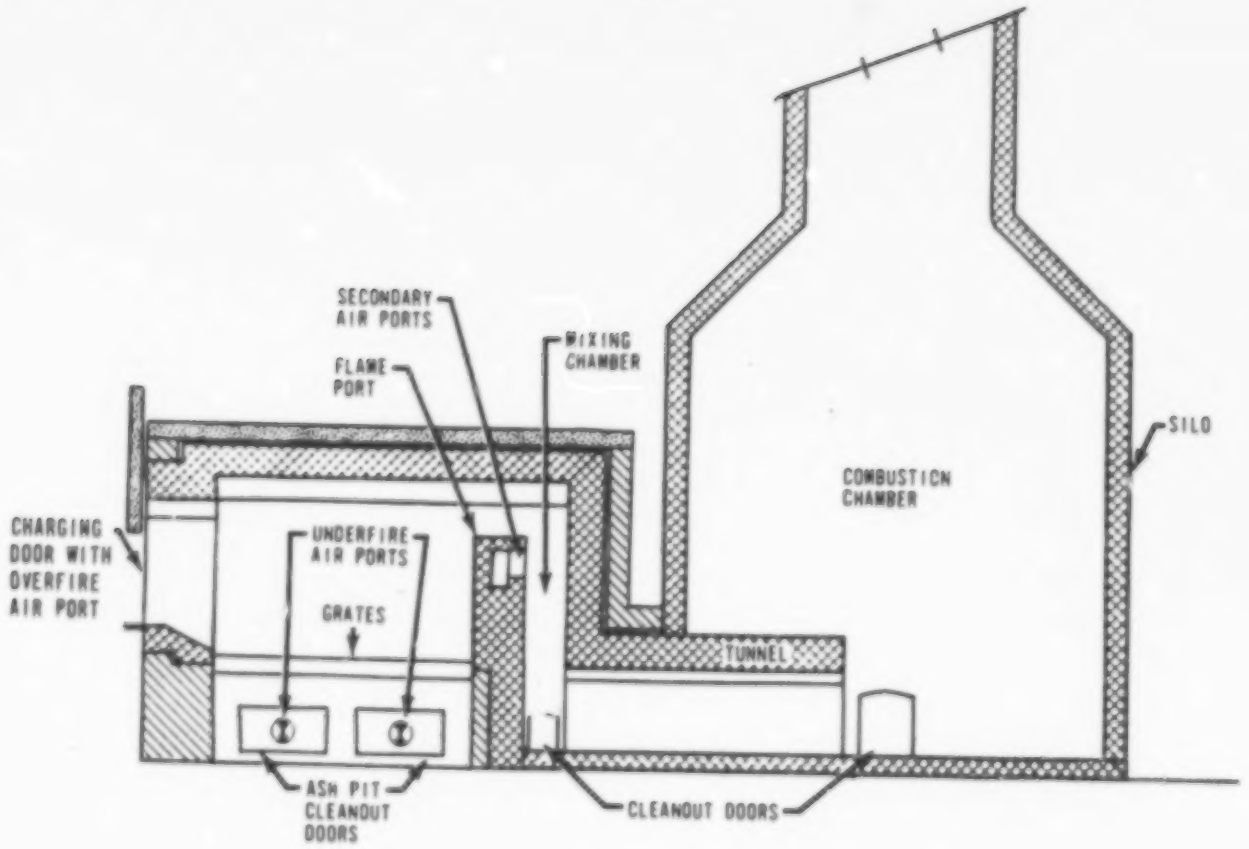


Figure 320. Schematic diagram of an in-line multiple-chamber incinerator (silo conversion).

In the design of the silo conversion, the size of the ignition chamber and mixing chamber attached to an existing silo is limited by a maximum allowable gas velocity of 10 fps through the horizontal cross-sectional base of the silo, or by the effective draft developed by the stack. Effective draft, in turn, is limited by the height of the silo and its internal dimensions.

If the attachment of an ignition and mixing chamber to a silo results in a gas velocity through the base of the silo of less than 5 fps, a refractory tunnel with a cross-sectional area equal to the curtain wall port area should extend from the curtain wall halfway across the base of the silo. The tunnel acts as an extension of the mixing chamber and provides additional flame residence time and turbulence necessary to complete the combustion process.

DESIGN PROCEDURE FOR MECHANICAL FEED SYSTEMS

During the development of the multiple-chamber incinerator, hand charging of sawdust and intermittent delivery of sawdust from local exhaust systems serving woodworking equipment were found to smother the flames periodically in the ignition chamber and thus cause excessive smoke. To overcome this problem, a feed system was developed for delivering small wood particles to the ignition chamber at a constant rate and thus sustain continuous burning over the entire surface of the pile. This system, illustrated in Figure 321, consists basically of a surge bin for holding sawdust and wood chips from local exhaust systems serving woodworking equipment. Screw or drag conveyors in the bottom of the surge bin move the wood waste at a uniform rate to the pickup point of a pneumatic conveying system. The pneumatic conveyor transfers the waste to a cyclone where the waste drops into the ignition chamber.

Surge Bin

Bins usually fabricated of sheet metal are designed in such a way as to augment gravity flow of sawdust and wood chips to the conveyor at the bottom of the bin. Waste is produced in a wide variety of sizes and shapes, ranging from fine sander dust to large chips from hoggers. Gravity flow of material is a complex function of the composition, size, shape, density, packing pressure, adhesive qualities, and moisture content. For example, pine wood shavings do not flow as easily as hardwood shavings of identical size and shape do because the resin content of the pine wood imparts an adhesiveness hindering the flow. The flow characteristics of a particular wood waste are, therefore, of primary importance in the final selection of the shape of the bin.

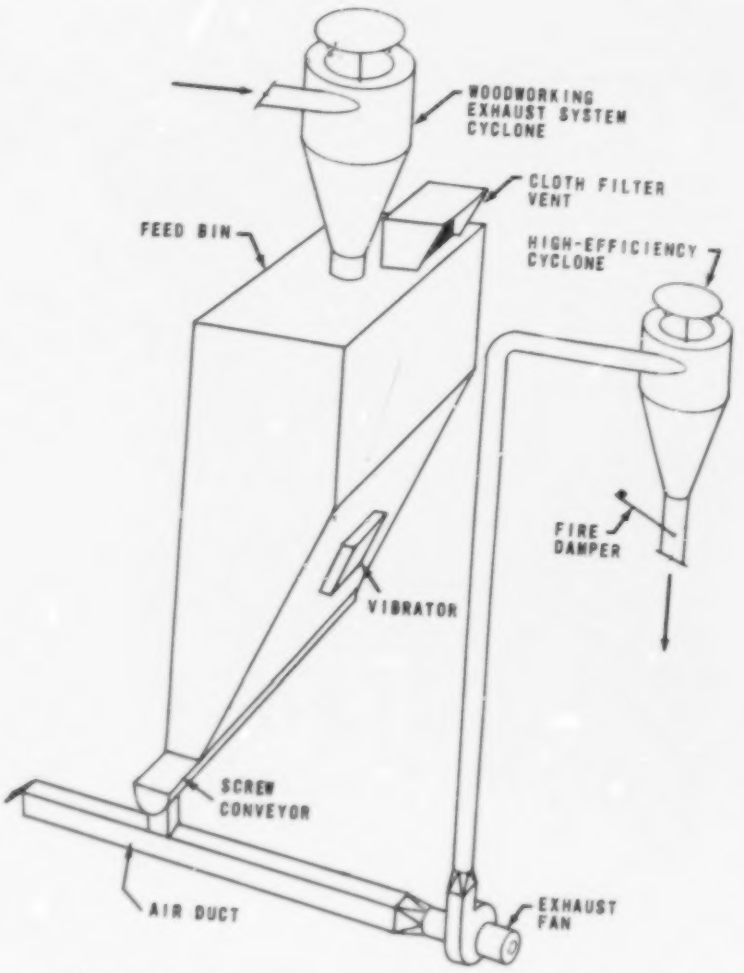


Figure 321. Diagram of a mechanical feed system.

Wood wastes that exhibit poor flow characteristics should be handled in bins constructed with vertical sides and screw or drag conveyors covering the entire flat bottom of the bin, as shown in Figure 322. If the wood waste has fairly free flow characteristics, a bin with four vertical sides and a sloping bottom may be used, as shown in Figure 323. The included angle between the vertical side and sloping bottom should not exceed 45 degrees. Wood waste that exhibits ideal flow characteristics may use a vee-bottom bin, as depicted in Figure 324. The included angle between sloping sections should not exceed 60 degrees for most efficient operation.

Although good bin design assists the flow of sawdust to the conveyors, bins with sloping bottoms require mechanical agitators or vibrators to prevent bridging. Vibrators are generally superior for this purpose since reciprocating and rotating bar agitators tend to shear and bend out of shape under heavy loads. To be most effective, vibrators are usually mounted about one-fourth of the distance from the base of the sloping bottom of the bin, which is usually constructed of a large, unsupported section of sheet metal. This method of construction permits transmission of vibration more easily than

transmission from sloping sections rigidly supported with stiffened angles or steel structural members. If the bottom is so large as to require some type of external cross-sectional support, the support members should be attached only at the edges of the section.

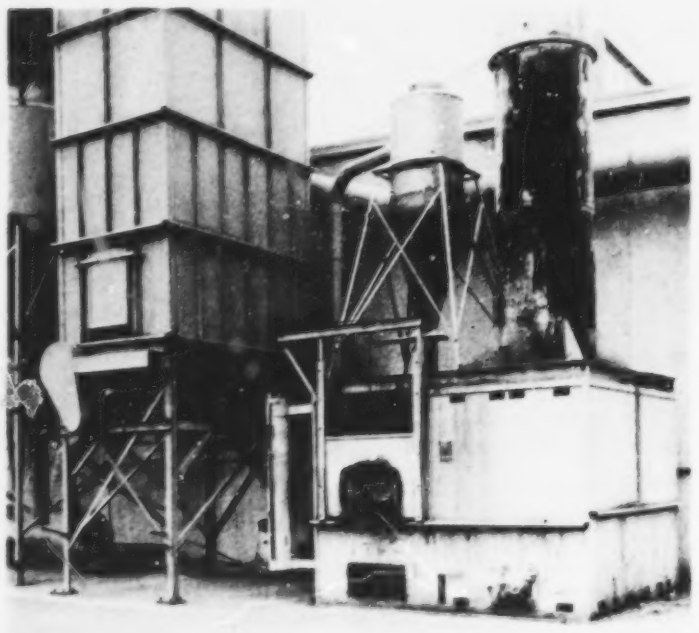


Figure 322. Vertical-sided feed bin with four parallel screw conveyors (Brown Saltman Furniture Co., Los Angeles, Calif.).

Vibrators operating continuously may cause the wood waste to pack and bridge in the bottom of the bin. To remedy this condition, the frequency of vibration or the amplitude of the vibratory stroke may be changed, or a mechanical timer may be installed to actuate the vibrators at desired intervals.

Screw or Drag Conveying

Screw or drag conveyors are placed in the bottom of a feed bin to remove sawdust and shavings from the bin at a regulated rate. Screw conveyors are preferred, except where long, tough, fibrous shavings are to be conveyed. Since material such as this would bind in conveyor flights, the more expensive drag conveyor must be used.

Screw conveyors with variable pitch are recommended over screws with uniform pitch because they permit more even loading of the screw along the entire length and thus minimize the compressing of sawdust and shavings causing bridging above the discharge end of the screw. Because relatively large pieces of wood may enter the conveying system, screw conveyors should be at least 6 inches in diameter to ensure their passage.

Regulation of the flow of wood waste is dependent upon the bulk density of the waste to be handled as well as upon the number, diameter, and speed of the screw conveyors. The bulk density of most wood wastes varies from 4 to 12 pounds per cubic foot, depending upon the kind of wood processed and the shape of the particles. Determination of the density must be based upon sawdust in its compressed form at the bottom of the bin, rather than in a loose form. Once the density has been established, the type of bin selected, and number of screws determined, the diameter and speed of the screws can be calculated. Provisions should also be made for a gear head or varidrive to regulate the speed of the conveyors so that they supply wood waste over a range of 33 to 100 percent of the burning capacity of the incinerator.

To prevent sawdust from being aspirated into the pneumatic conveying system faster than the normal delivery rate of the screw, conveyors should extend at least three screw diameters beyond the end

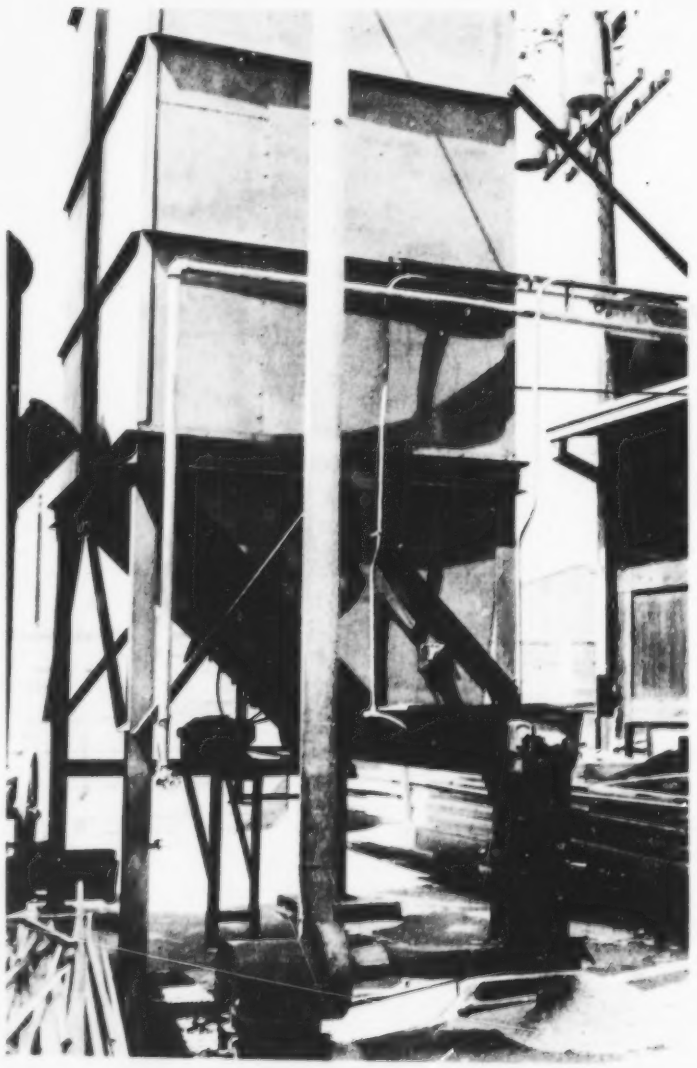


Figure 323. Feed bin with sloping bottom (California Moulding and Trim Mfg. Co., Los Angeles Calif.).

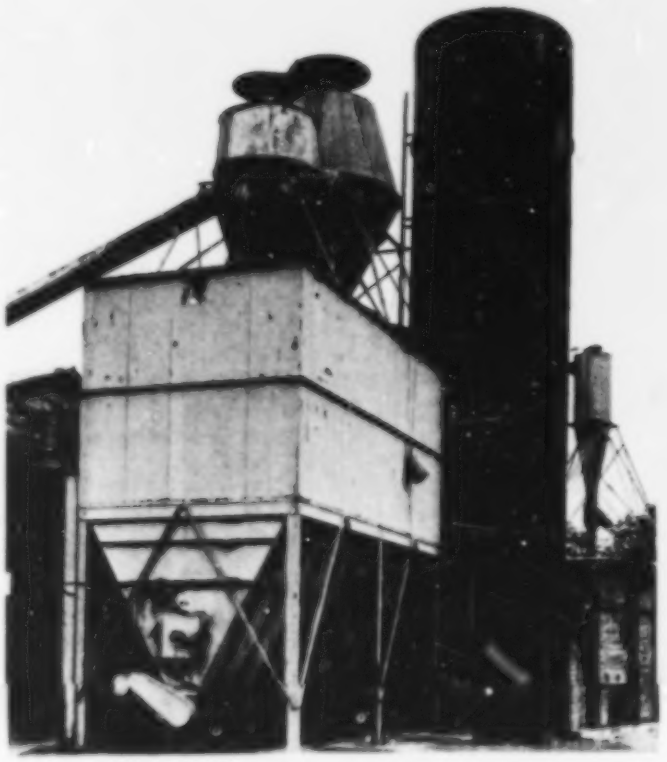


Figure 324. Feed bin with vee bottom (Orban Lumber Co., Pasadena, Calif.).

of the bin, and the shrouds should be installed over the extended section, as shown in Figure 325. Shrouds are usually adjusted after the unit is in operation, to provide optimum clearance over the flights and prevent binding.

Pneumatic Conveying

While general design features for pneumatic conveying systems are discussed in the preceding chapter, a number of specific features should be considered in designing pneumatic conveying systems for wood waste incineration.

Pneumatic conveying systems are generally designed for a ratio of 2/3 cfm of conveying air per hour per pound of sawdust to be burned. About 10 percent of this conveying air should be admitted to the incinerator along with the wood waste to assist in spreading the particles evenly over the entire grate area and to maintain active flame over the surface of the burning pile. The amount of conveying air entering the ignition chamber may be regulated by installing either a butterfly damper in the top outlet duct of the cyclone separator, or spiral vanes within the cone of the cyclone separator.

Sawdust pickup and conveying velocities should be at least 3,000 fpm to prevent sawdust blockage in the ductwork. Blower motors should be oversized to accommodate occasional surges of sawdust through the pneumatic conveying system.

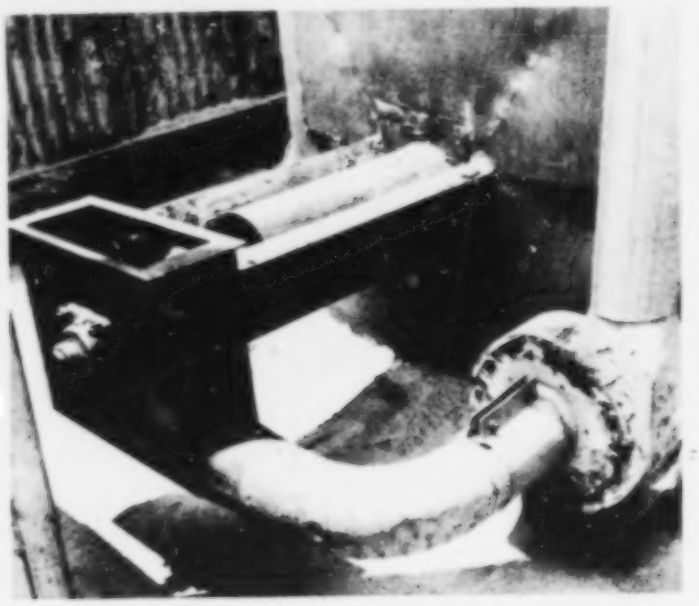


Figure 325. Screw conveyor with shroud (Acme Woodcraft, Los Angeles, Calif.).

Cyclone separators used in conjunction with the blower are of the small-diameter, high-efficiency type with separation factors that exceed 100, as described in Chapter 4.

A flap-type damper equipped with a counterbalance weight should be installed at the bottom outlet of the cyclone separator. This damper is adjusted to close automatically when the blower is not in operation, which prevents the hot gases of the ignition chamber from damaging the sheet metal of the cyclone separator and also prevents smoke from being emitted to the atmosphere from the top of the cyclone. This damper should be constructed of 1/4-inch stainless steel plate since it is subject to intense radiation from the burning pile. By construction of a square-shaped damper with a square duct extending below, the damper is able to swing out of the way of the falling wood waste. The damper should be large enough to form a tight, overlapping seal with a smooth, stainless steel flange located below the round duct at the bottom of the cyclone separator.

To ensure proper operation, the equipment should be electrically interlocked to start simultaneously or in the following order: (1) Blower, (2) conveyors, (3) vibrators or agitators.

STANDARDS FOR CONSTRUCTION

While structural features of wood-burning incinerators are similar to those of general-refuse incinerators, wood-burning incinerators must be designed for greater stresses and strains caused by increased thermal expansion resulting from higher temperature operation. Refractories, therefore, are selected to resist not only normal abrasion

from charging but also erosion, spalling, and slagging resulting from high-temperature, high-velocity flame impingement.

Refractories

Super-duty plastic refractory or super-duty fire clay firebrick are recommended for the interior walls and arches that come into direct contact with flames and hot gases, since temperatures usually exceed 2,000°F. Expansion joints with 1/2-inch minimum width should be installed for every 6-foot section of refractory. These joints must be sealed completely with high-duty ceramic packing with minimum service temperatures of 2,500°F. Packing of this type is necessary to prevent ashes from collecting in the open joints and fusing in such a way as to render the joint useless.

The first 10 feet of stack must be lined with high-duty firebrick or an equivalent castable refractory. The remainder of the stack may be lined with a lower duty material since flame impingement in this area does not normally occur. The charging door and other access doors, with the exception of the ash pit cleanout doors, should be lined with 120-pound-per-cubic-foot, ASTM Class 24, castable refractory.

The minimum heights for free-standing firebrick walls of given thickness are as follows.

Thickness of walls, in.	Unsupported height, ft
4-1/2	4
9	10
13-1/2	14

Firebrick walls extending above these heights should be held to exterior supports with stainless steel anchors that permit a differential rate of expansion. Walls constructed of plastic refractory should be anchored to exterior structural steel members on 18-inch centers.

Arches may be constructed of firebrick or plastic refractory. Firebrick arranged to form 60-degree arches should be limited to a maximum span of 5 feet 10 inches for 4-1/2-inch thickness and 8 feet for 9-inch thickness. Arches with spans greater than 8 feet should be constructed of suspended, super-duty, fire clay shapes or super-duty, plastic refractory. Plastic refractory used for this purpose must be suspended from refractory cones or stainless steel anchors spaced not more than 15 inches apart.

Grates

Two materials satisfactory for construction of grates are cast iron and castable refractory. Cast iron grates are available in a wide variety of sizes and shapes. They are of much heavier construction than those used in comparable general-refuse incinerators, to minimize deformation at high temperatures. Where blocks or scraps of wood are to be burned, bar- or channel-shaped grates should be employed, but when wood waste accumulated from woodworking equipment is to be burned, pinhole grates should be installed. Typical pinhole grates consist of 6-inch-wide by 24-inch-long by 3/4-inch-thick slab sections of cast iron with 1/2-inch holes on 2-inch centers. Grates of this type are capable of retaining small wood particles that might otherwise fall unburned into the ashpit.

Refractory grates are nearly always constructed in the form of 60-degree sprung arches. On incinerators of 250-pound-per-hour capacity or less, grates are constructed of ASTM Class 24 refractory 5 to 6 inches thick, with 1-inch holes on 5- to 6-inch centers. ASTM Class 27 castable refractory 6 to 8 inches thick, with 1-inch holes on 6- to 9-inch centers is used in larger incinerators.

Caution is required in operating incinerators with cast iron grates. Underfire air must not be unduly restricted nor should the ash pit be allowed to fill within 1 foot of the grates. Heat buildup in the ash pit from either condition can cause the grates to warp and sag. Misoperation of this type does not deform grates constructed of castable refractory. These grates are, however, susceptible to damage from careless stoking and cleaning.

When most of the charge consists of sawdust or similar small wood particles delivered by a uniform feed system, a solid hearth should be installed at the rear of the ignition chamber to prevent the introduction of excessive underfire air at this location. As the size of the incinerator increases, hearths are sometimes installed along the sidewalls also to prevent excessive underfire air. In any event, the hearth area should not exceed 30 percent of the total horizontal area of the primary ignition chamber.

Exterior Walls

Incinerators can be constructed with exterior walls of red brick or steel plate. Red brick exteriors are usually constructed of two layers of red brick bonded by a reinforced concrete center. Exterior steel plate may be of the thin, corrugated type used to back plastic refractory, or as heavy as 10 gauge to support interior brick construction.

Air Ports

Combustion air port controls should be constructed of cast iron not less than 1/2 inch thick. These ports should fit tightly to reduce air leakage to a minimum.

OPERATION OF INCINERATORS

Certain differences exist between the operation of wood-burning incinerators and general-refuse incinerators. The operator of a general-refuse incinerator generally relies on auxiliary burners to maintain temperatures for maximum combustion in the secondary chamber. The operator of a wood-burning incinerator, without provisions for auxiliary burners, is able to maintain adequate secondary chamber temperatures by proper charging and control of combustion air.

Generous amounts of clean dry paper are mixed with the wood for the initial charge. After the ignition chamber is one-half to two-thirds full, additional paper is placed on top of the pile to ensure quick flame coverage at the surface. It is important, in keeping smoke to a minimum, that only clean dry paper and dry scrap wood comprise the initial charge. After charging is completed, the paper is ignited near the front of the chamber and the charge door is closed. All combustion air ports are almost completely closed to restrict combustion air.

As burning proceeds, the incinerator passes through the most critical period of its operation. By observing the emissions from the stack, the necessary adjustments can be made promptly to reduce or eliminate smoke. Gray or white smoke emitted after lightoff indicates that the incinerator is cold. This smoke can be minimized or eliminated by closing all air ports. Smoke of this color usually ceases within a few minutes after lightoff when flames completely cover the refuse pile and fill the flame port. A few minutes later, black smoke may appear, resulting from a lack of adequate combustion air. These emissions can usually be eliminated by opening primary air ports and then the secondary air ports. If additional combustion air is required, it may be supplied by opening the charge door.

Although each incinerator has its own operating characteristics, the overfire and underfire air ports can usually be opened 5 to 10 minutes after lightoff, and the secondary port, 20 to 30 minutes later. If opening of the secondary ports results in gray or white smoke emissions, the ports should be closed immediately since the incinerator has not yet reached its normal operating temperature.

After attaining normal operating temperatures, maximum combustion is maintained by placing the mechanical feed system in operation or by hand charging at regular intervals.

Illustrative Problem

Problem:

Design a multiple-chamber incinerator to burn 1,000 pounds of Douglas fir waste per hour with a maximum moisture content of 10 percent.

Solution:

1. Composition of the refuse:

Dry combustibles	(1,000 lb/hr)(0.90) =	900 lb/hr
Moisture	(1,000 lb/hr)(0.10) =	100 lb/hr
Total		1,000

2. Gross heat input:

From Table 118, the gross heat of combustion of 1 pound of dry Douglas fir is 9,050 Btu/lb

(900 lb/hr)(9,050 Btu/lb) = 8,140,000 Btu/hr

3. Heat losses:

(a) Assume radiation, convection, and storage heat losses are 20 percent of gross heat input:

(0.20)(8,140,000 Btu/hr) = 1,625,000 Btu/hr

(b) Evaporation of contained moisture:

The gross heat of vaporization of water at 60°F is 1,060 Btu/lb

(100 lb/hr)(1,060 Btu/lb) = 106,000 Btu/hr

(c) Evaporation of water formed by combustion:

From Table 118, there is 0.563 lb of water formed from the combustion of 1 pound of dry Douglas fir.

$$(900 \text{ lb/hr})\left(\frac{0.563 \text{ lb } H_2O}{\text{lb}}\right)(1,060 \text{ Btu/lb})$$

= 537,000 Btu/hr

(d) Total heat losses:

a + b + c = total losses

1,625,000 Btu/hr + 106,000 Btu/hr +

537,000 Btu/hr = 2,268,000 Btu/hr

4. Net heat available:

8,140,000 Btu/hr - 2,268,000 Btu/hr =

5,872,000 Btu/hr

5. Weight of products of combustion:

From Table 118, there is 13.86 lb of combustion products from 1 pound dry Douglas fir

with 100 percent excess air, and 20.30 lb of combustion products from 1 pound dry Douglas fir with 200 percent excess air. Weight of products of combustion at 100 percent excess air:

Wood	(900 lb/hr)(13.86 lb/lb) =	12,450 lb/hr
Moisture	(100 lb/hr)	100 lb/hr
		12,550 lb/hr

Weight of products of combustion at 200 percent excess air:

Wood	(900 lb/hr)(20.30 lb/lb) =	18,200 lb/hr
Moisture	(100 lb/hr)	100 lb/hr
		18,300 lb/hr

6. Average gas temperature at 200 percent excess air:

$$Q = w_p c_p (T_2 - T_1)$$

where:

Q = net heat available, Btu/hr

w_p = weight of products of combustion, lb/hr

c_p = specific heat of products of combustion, Btu/lb-°F

T_2 = average gas temperature, °F

T_1 = initial temperature, °F

$$T_2 = T_1 + \frac{Q}{(w_p)(c_p)}$$

$$T_2 = 60°F + \frac{5,872,000 \text{ Btu/hr}}{(18,300 \text{ lb/hr})(0.26 \text{ Btu/lb-°F})}$$

$$= 1,300°F$$

7. Combustion air port areas:

(a) Primary air port sizes:

Assume primary air at 100 percent excess.

From Table 118, 179.6 scf of air is required per pound of dry Douglas fir

(900 lb/hr)(179.6 scf/lb) = 161,800 scfh

or 2,700 scfm

Assume the average air velocity through the primary air ports is 900 fpm or 0.052 in. WC velocity pressure.

$$\text{Area} = \frac{2,700 \text{ scfm}}{900 \text{ fpm}} = 3.00 \text{ ft}^2$$

or 432 in.^{2}

Overfire air port area:

Assume overfire air port area is 90 percent of total.

(0.90)(432 in.^{2}) = 388 in.^{2}

Underfire air port area:

Assume underfire air port area is 10 percent of total.

(0.10)(432 in.^{2}) = 43 in.^{2}

(b) Secondary air ports located in the bridge wall and curtain wall:

Assume 50 percent theoretical air through each port.

From Table 118, 42.37 scf of air is required per pound of dry Douglas fir.

(900 lb/hr)(42.37 scf/lb) = 38,100 scfh

or 634 scfm

Average air velocity through secondary ports is assumed to be 1,000 fpm or 0.063 in. WC velocity pressure.

$$\text{Area} = \frac{634 \text{ scfm}}{1,000 \text{ fpm}} = 0.63 \text{ ft}^2$$

or 91 in.^{2}

8. Volume of products of combustion:

(a) Volume through flame port:

Assume 100 percent excess air through flame port.

From Table 118, there is 179.6 scf of products of combustion from 1 pound dry Douglas fir.

Wood

(900 lb/hr)(179.6 scf/lb) = 161,000 scfh

Moisture

$$(100 \text{ lb/hr}) \frac{379 \text{ scf/lb mole}}{18 \text{ lb/lb mole}} = \frac{2,100 \text{ scfh}}{163,100 \text{ scfh}}$$

or 2,720 scfm

or 45.4 scfs

(b) Volume through mixing chamber:

Assume 50 percent theoretical air is added through secondary port to combustion products from primary chamber.

(900 lb/hr)(42.37 scf/lb) = 38,100 scfh

or 10.6 scfs

Total volume = 45.4 scfs + 10.6 scfs = 56.0 scfs

(c) Volume through combustion chamber:

Assume 50 percent theoretical air is added through cooling air ports in curtain wall.

Total volume = 56.0 scfs + 10.6 = 66.6 scfs

9. Incinerator cross-sectional areas:

(a) Flame port area:

From Table 120, design for an average velocity of 50 fps and 1,900°F gas temperature:

$$\text{Area} = \frac{(45.4 \text{ scfs})(2,360°\text{R})}{(50 \text{ fps})(520°\text{R})} = 4.12 \text{ ft}^2$$

(b) Mixing chamber cross-sectional area:

From Table 120, design for an average velocity of 25 fps and 1,550°F gas temperature:

$$\text{Area} = \frac{(56.0 \text{ scfs})(2,010°\text{R})}{(25 \text{ fps})(520°\text{R})} = 8.65 \text{ ft}^2$$

(c) Curtain wall port area:

From Table 120, design for an average velocity of 20.0 fps and 1,500°F gas temperature:

$$\text{Area} = \frac{(56.0 \text{ scfs})(1,960°\text{R})}{(20.0 \text{ fps})(520°\text{R})} = 10.5 \text{ ft}^2$$

(d) Combustion chamber cross-sectional area:

From Table 120, design for an average velocity of 7.5 fps and 1,200°F gas temperature:

$$\text{Area} = \frac{(66.6 \text{ scfs})(1,660°\text{R})}{(7.5 \text{ fps})(520°\text{R})} = 28.4 \text{ ft}^2$$

(e) Stack area:

From Table 120, design for a velocity of 20 fps and 1,100°F gas temperature:

$$\text{Area} = \frac{(66.6 \text{ scfs})(1,560°\text{R})}{(20 \text{ fps})(520°\text{R})} = 10.0 \text{ ft}^2$$

10. Grate area:

From Figure 310, the grate loading is 33 lb/hr-ft^2 for the upper +10 percent curve used for 9,000 Btu/lb refuse.

$$\text{Total grate area } \frac{(1,000 \text{ lb/hr})}{33 \text{ lb/hr-ft}^2} = 30.3 \text{ ft}^2$$

11. Horizontal dimensions of ignition chamber:

From Table 120, length-to-width ratio = 1.5

Let W = width and L = 1.5W

Then $(W)(1.5W) = 30.3 \text{ ft}^2$

$1.5W^2 = 30.3$

$W^2 = 20.1$

Width = 4.5 ft

Length = (1.5)(4.5) = 6.75 ft

12. Arch height:

From Figure 311, the arch height for the upper +10 percent curve is 5 ft.

13. Stack height:

From Figure 312, stack height above grade is 35 ft.

FLUE-FED APARTMENT INCINERATORS

INTRODUCTION

An incinerator in which the chimney also serves as a chute for refuse charging, as shown in Figure 326, is known as a flue-fed incinerator (MacKnight et al., 1960). For some 40 years the single-chamber, flue-fed incinerator has been built as an integral part of apartment buildings. The incinerator is usually located centrally in the building to minimize the distance from the apartments to the charging chutes located on each floor. Occasionally the incinerator may be located on an outside wall with charging chutes outside the building and adjacent to a balcony or fire escape platform. The flue-fed incinerator is also used to some extent in schools, hospitals, and office buildings.

The single-chamber, flue-fed incinerator has a box-like combustion chamber separated by dump grates from an ashpit below. Atmospheric gas burners located below the grates are used primarily for dehydration of garbage and other wet material. A cleanout door is provided for removal of ashes from the ash pit. A charging door above the grates is used for igniting the refuse and for stok-

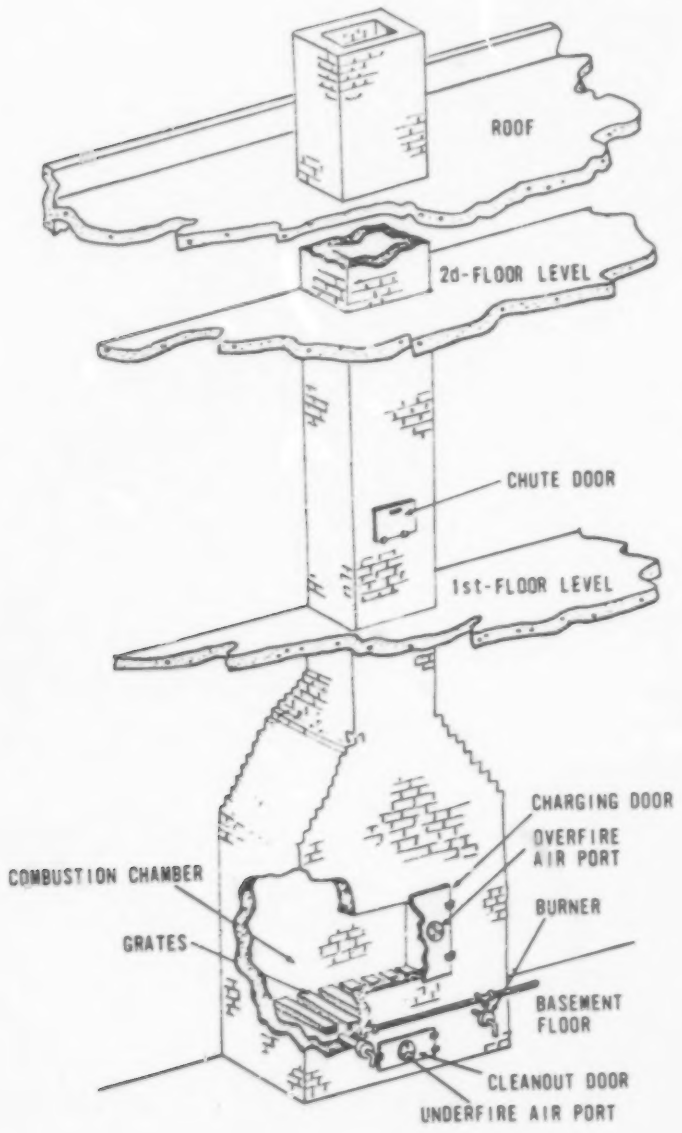


Figure 326. Unmodified flue-fed incinerator (MacKnight et al., 1960).

ing the burning pile near the end of the burning period. In most instances both doors are provided with spinners to allow admission of underfire (undergrate) and overfire (overgrate) air. The walls of the incinerator are customarily constructed of two layers of brick. The inner layer consists of 4-1/2 inches of firebrick separated by a 1/2-inch airspace from a 9-inch common brick exterior. The flue is normally constructed of 9 inches of common brick with a 1-inch flue tile lining. The inside dimensions of the flue are usually 16 by 16 inches for apartment buildings 3 to 4 stories in height.

Description of Refuse

The composition (% by wt, minimum to maximum) of apartment house refuse usually falls within the following limits: Dry paper, 50 to 100; garbage, 0 to 30; plastics, 0 to 3; noncombustibles, 2 to 10; and other (including rags, waxed cartons, greenery, and so forth), 0 to 10. If food is prepared in the apartments the percent of garbage, plastics, waxed cartons, and noncombustibles in refuse approaches the upper limits. If food is not prepared on the premises then the refuse is more likely to have a higher percentage of dry paper. An average value taken by incinerator designers for the production of refuse by apartment dwellers is 1 pound per person per day.

THE AIR POLLUTION PROBLEM

When first ignited, refuse in a flue-fed incinerator burns very rapidly. Air inspiration during this initial flash burning period is usually insufficient to meet the combustion requirements of the rapidly burning dry refuse, resulting in incomplete combustion and black smoke emissions. The concurrent extreme gas turbulence results in the entrainment of large quantities of fly ash (ash and charred paper).

Once the initial flash burning period has passed, an excessive draft develops as a result of the high flue gas temperature and the long flue. The amount of air admitted through the air ports becomes greater than the demand for combustion air, and the temperature in the combustion chamber gradually diminishes as the excess air increases. As this process continues, the combustible gases, oils, tars, and fats, produced by low-temperature combustion at the surface of the refuse pile and by destructive distillation within the pile, pass out the stack incompletely burned in the form of white or light gray smoke.

The use of undergrate burners tends to entrain fly ash in the hot gases passing through and around the fuel bed. This problem is further aggravated by stoking of the burning refuse pile under excessive draft conditions, resulting in the discharge of large quantities of fly ash from the stack. The problem is compounded by the charging of refuse down the flue during the burning period, which smothers and scatters the burning pile and results in severe fly ash emissions and smoke production.

Stack Emissions

The range of particulate emissions found by a series of tests, in pounds per ton of refuse burned, is shown in Table 121. Associated data are included in the table as a matter of general interest. Other, less plentiful data indicate that emissions (in pounds per ton) are as follows: organic acids, 9.5; aldehydes, 1.5; hydrocarbons, 2; and nitrogen oxides, 6.

AIR POLLUTION CONTROL EQUIPMENT

There are three basic methods of altering a flue-fed incinerator to prevent the discharge of air con-

Table 121. PARTICULATE EMISSIONS FROM TYPICAL FLUE-FED INCINERATORS

Test designation	Particulate matter, lb/ton	Particulate matter, gr/scf at 12% CO_2	Particulate matter, gr/scf	Average stack volume, scfm	Grate area, ft^2	Stack height, ft
C-95	76	2.27	0.61	458	1.5	25
652	52	1.40	0.13	1,190	16	35
881	48	1.60	0.21	326	9	68
C-116	37	1.40	----	213	5	32
D-3	37	1.18	0.20	820	12	80
D-2	34	1.06	0.21	930	12	80
C-699-1	25	0.94	0.18	500	6	54
650	23	0.99	0.10	1,120	12	56
D-1	23	0.75	0.2	860	12	80
C-45	19	0.75	0.26	530	4	25
C-50	17	0.60	0.09	441	20	56
C-46	7	0.27	0.08	917	8	46

taminants. Two of these methods involve the addition of an afterburner to the existing incinerator. The third method involves the installation of a well-designed multiple-chamber incinerator. Appurtenances for regulating stack draft and effectively controlling the charging during the burning period are essential to these methods.

INSTALLATION OF AFTERBURNER ON A ROOF

A typical installation of an afterburner on a roof includes the use of a damper located at the base of the stack to control the excessive draft and burning rate, and an afterburner mounted on top of the existing stack to control the smoke and combustible gases. Chute door locks are installed to prevent damage to the draft control damper from the charging of refuse during the burning period.

Design Procedure

Draft control

The excessive draft conditions prevailing in flue-fed incinerators must be reduced before an afterburner will function successfully. A swinging, counterweighted damper can be used for draft control by pivoting it on a rod along one edge so that it can be swung flush with one wall of the flue to permit charging of refuse. Swung back into a horizontal position, the damper can maintain the draft in the basement combustion chamber within suitable limits. This damper is equipped with adjustable openings in its surface since the exact restriction required for a specific unit cannot be determined. By changing the location of the adjustable plates fastened to the surface of the damper, the size of the openings can be decreased until the desired draft, usually from 0.10 to 0.20 inch WC, is attained. These dampers are located in the flue beneath the first-floor chute door to ensure a negative pressure at each door and thus prevent smoke and sparks from blowing by the doors into the building.

The effect of a damper on combustion chamber draft, burning rate, and flue gas velocity is shown in Figures 327, 328, and 329. These graphs were obtained by testing a 6-story, flue-fed incinerator equipped with a draft control damper having a 6-1/2-inch-diameter orifice and afterburner. The curves in the graphs designated "uncontrolled flue-fed incinerator" were obtained by operating the incinerator with the damper open and the afterburner off.

Figure 327 shows the draft in the combustion chamber of the incinerator to be lower and more stable when the damper is in use. Figure 328 shows that the initial peak burning is considerably reduced when the damper is used. Figure 329 shows that the flue gas velocities are lower when the draft control damper is used.

The lower draft condition in the combustion chamber, attained from the use of a draft control damper, minimizes the entrainment of fly ash in the flue

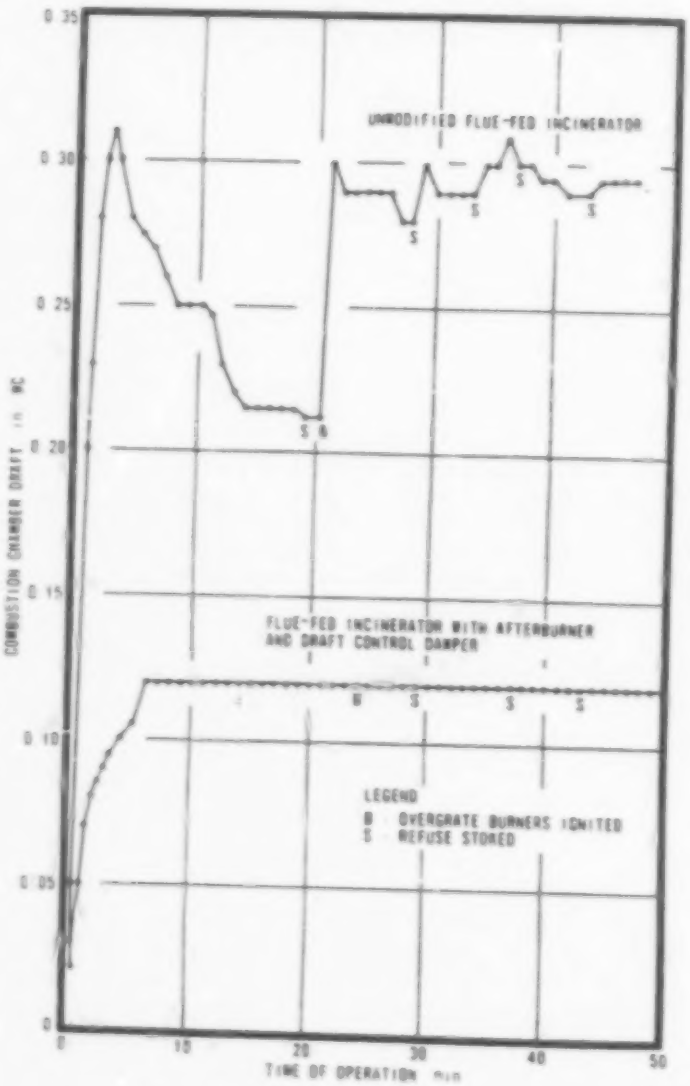


Figure 327. Draft in combustion chamber of modified and unmodified flue-fed incinerators (MacKnight et al., 1960).

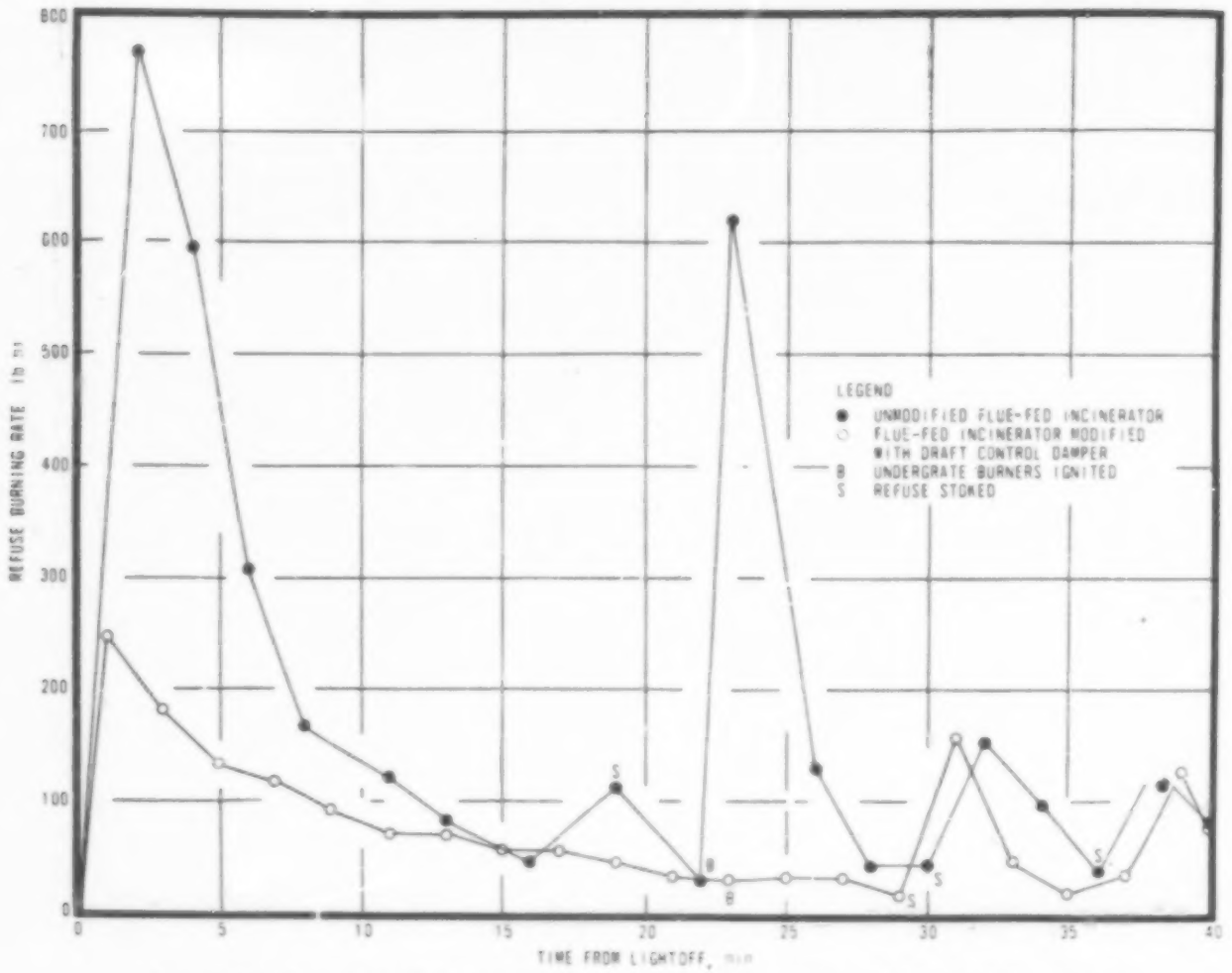


Figure 328. Burning rate versus time for modified and unmodified flue-fed incinerators.

gases. This condition also reduces the burning rate, permitting the use of a smaller afterburner than otherwise would be required. Installation and operating costs of the afterburner are accordingly reduced.

Chute door locks

The charging of refuse during the burning period can be prevented easily and economically by installing solenoid locks on each of the chute-charging doors. The use of this type of lock permits their actuation from a single switch in the basement before the damper is closed and the burning cycle begins.

If refuse is charged down the flue during the burning period when the draft-controlling damper is closed, several undesirable events may occur. The damper may be bent, or even detached from its supports, or the refuse may pile up on the damper and block the flue, causing the gases from the refuse burning in the combustion chamber to vent into the basement. Chute door locks prevent these problems in addition to preventing smothering of the refuse pile and the subsequent creation of smoke and fly ash.

Design parameters

Parameters for roof afterburners are essentially the same as the parameters employed in designing afterburners for smokehouses, ovens, and so forth. For a discussion of appropriate parameters relating to retention time, mixing of gases, gas velocities, temperature levels, flame characteristics, and burner types and arrangements, see the first part of Chapter 5.

Limitations

Most flues are not airtight since cracks develop with age and use. In particular, relatively large openings occur around the chute doors.

Air inspirated in this manner mixes with the flue gases and passes through the afterburner. Additional air entering the afterburner lowers exit gas temperatures, increases gas velocities, and reduces residence times. Thus, this overall effect reduces the efficiency of the afterburner.

As the height of the building increases, the air induced into the flue also increases. No definite building height limitation can be given since air

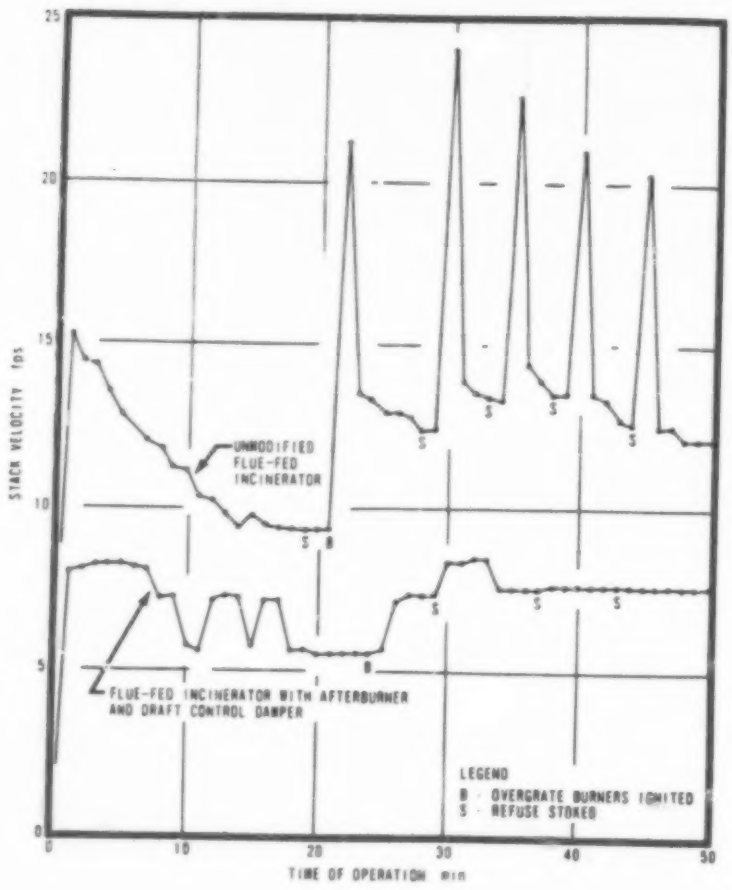

STACK VELOCITY fps
TIME OF OPERATION min
UNMODIFIED FLUE-FED INCINERATOR
FLUE-FED INCINERATOR WITH AFTERBURNER AND DRAFT CONTROL DAMPER
LEGEND
B - OVERGRATE BURNERS IGNITED
S - REFUSE STOKED

Figure 329. Flue gas velocity at inlet of afterburner of modified and unmodified flue-fed incinerators (MacKnight et al., 1960).

leakage increases in importance with increasing height. As of 1963, however, a 9-story building is the tallest building in Los Angeles County on which a roof afterburner has been successfully employed.

Typical installations

Figures 330 and 331 are cutaway drawings of two typical afterburners mounted on flue-fed incinerators. The inner passage of the afterburner in Figure 330 is built in the shape of a lazy L. A premix gas burner fires horizontally into the passage just below the L. The inclined section above the burner provides an impingement surface for the burner flames and also deflects the effluent from its vertical path. Mixing of the flames and flue gases beneath the inclined section has proved adequate to burn the contaminants in the incinerator gases.

The afterburner shown in Figure 331 consists basically of a ring burner followed by a venturi throat, a baffle to ensure contact between burner flames and flue gases, and a combustion chamber. The flue gases enter the afterburner through the ring burner. The cross section of the burner ring is

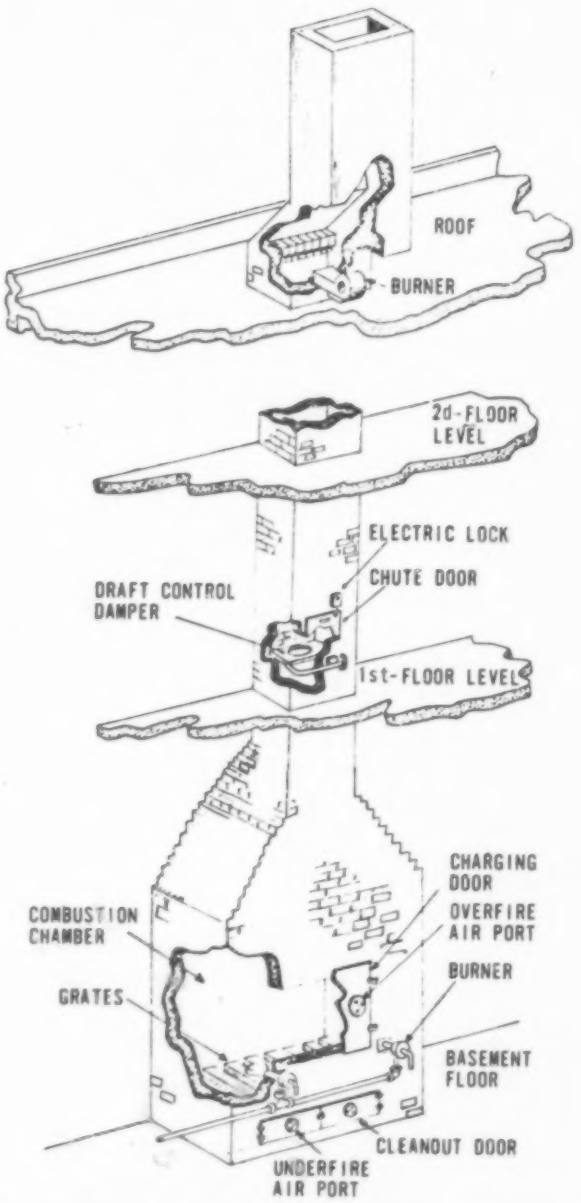


Figure 330. Flue-fed incinerator modified by a roof afterburner and a draft control damper.

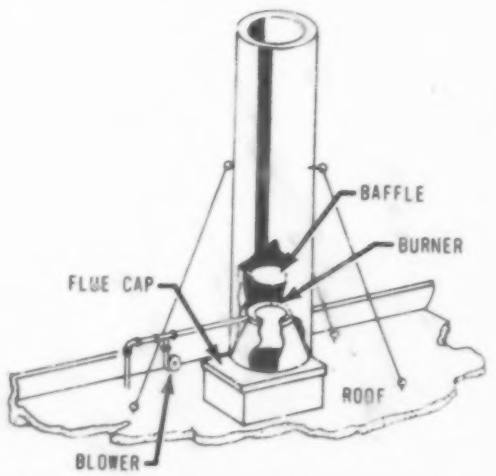


Figure 331. Flue-fed incinerator modified by a roof afterburner, and a draft control damper (Sargent Afterburner, Kearney, N.J.).

that of an isosceles right triangle, the hypotenuse connecting the two legs of the triangle forming the inside surface of the burner. Equally spaced orifices are located in this surface of the burner to create a conical flame pattern and yet prevent the flames from being extinguished by the rush of flue gases over its inner face.

The premix burner, venturi throat, and baffle are empirically sized to cause maximum mixing between the flue gases and burner flames consistent with minimum pressure loss through the afterburner. All smoke and unburned volatiles passing through the ring burner are brought into intimate contact with the flames. Additional combustion air may be supplied through openings below the burner in the wall of the afterburner. Because of the remote location of the afterburner, automatic spark ignition and complete flame failure controls are usually installed..

Standards for Construction

There are several reasons why the maintenance of a roof afterburner is likely to be inadequate. First, it operates in an unfrequented location. Second, responsibility for its operation and service is usually assigned to unskilled janitorial personnel. Third, its installation and use stem strictly from legal compulsion, and little attention is given over and above the minimum necessary to meet the requirements of the law. Consequently, an afterburner should be constructed of durable materials that require as little maintenance as possible.

Mounting and supports

The flue is dismantled to a height of 2 feet above the roof, and the afterburner is constructed on the flue above this point. Shortening the flue facilitates work on the unit, reduces windloading and earthquake stresses, and makes the completed unit less prominent.

One method successfully used to fasten the afterburner on the flue consists of bolting a 1/4-inch-thick steel plate to the flue and welding the afterburner shell to the plate. A central hole the size of the flue opening is, of course, first cut in the plate.

Additional support is usually provided by three 1/4-inch guy cables evenly spaced around the afterburner. The guys can be welded to the afterburner shell near its top and attached to the building by bolts going through the roof. In buildings constructed of wood, the bolts should enter the roof joists.

Metals

The following metals are recommended for use in afterburners because experience has shown that they resist deterioration under the conditions of their use. Sheet steel with a minimum thickness of 12-gage is recommended for use in fabricating afterburner shells. Stainless steel, type 321, 1/8-inch thick, is recommended for use in all afterburner baffles receiving direct flame impingement. Support rods for baffles should have a minimum diameter of 1/2 inch and should be made of type 321 stainless steel.

Castable refractories

Castable refractories used near the burner are invariably subjected to direct flame impingement. These linings should be at least ASTM Class 27 refractories with a minimum thickness of 4 inches. (Class 27 refractories are those castable refractories capable of withstanding temperatures of 2,700°F.) In addition, a 1-inch-thick backing of 1,000°F castable insulation or equivalent should be placed between the refractory and the metal shell. (The castable venturi throat in the afterburner of Figure 331 is so constructed.)

Castable refractory used to line the afterburner shell above the actual burning zone should have a minimum thickness of 2 inches. Class 24 castables, that is, those castable refractories capable of withstanding temperatures of 2,400°F, can be used in this area. A popular method of installing these linings consists of casting them in a ring shape and slipping them into the shell. Support for each castable section is derived from metal clips welded to the inner wall just below the first section of the shell. These clips fit into recesses provided in this castable section so that they are protected from the flames of the afterburner.

Firebrick

Of the four types of firebrick, only high-duty brick is normally used in afterburners. When used, it is generally limited to areas receiving direct flame impingement or high-temperature flame radiation. Lower duty castable refractories or insulating firebrick are normally used instead of firebrick in places of less severe duty.

Insulating firebrick

In areas of the afterburner without direct flame impingement, 2,000°F insulating firebrick may be successfully used. This type of brick is frequently used in 2-1/2-inch-thick rings to line the upper section of afterburners. (The stack above the venturi throat in the afterburner of Figure 331 is lined with this type of brick.) When cut into wedge shapes and arranged around the inner shell, the individual bricks lock into place and mortar need not be used.

Burners

A forced-draft gas burner such as that described in the second part of Chapter 9 should be used.

This type of burner supplies much of its own air needed for combustion. Since the amount of oxygen in the flue gas is less than that in a normal atmosphere, the ability to supply a significant portion of its own oxygen requirements is an important factor in burner selection.

Draft control damper

The draft control damper receives direct flame impingement from the refuse burning in the combustion chamber. For this reason, the damper must be constructed of stainless steel. Dampers of 20-gage type 302 stainless steel with 3/4 inch of each edge bent down to increase stiffness have proved satisfactory.

Chute door locks

Figure 332 shows a typical chute door lock installation. The lock shown is of the type that allows the door to be closed at all times without breaking the latch. This type of latch is recommended for use because it permits the door to be closed during the incinerator's operation.

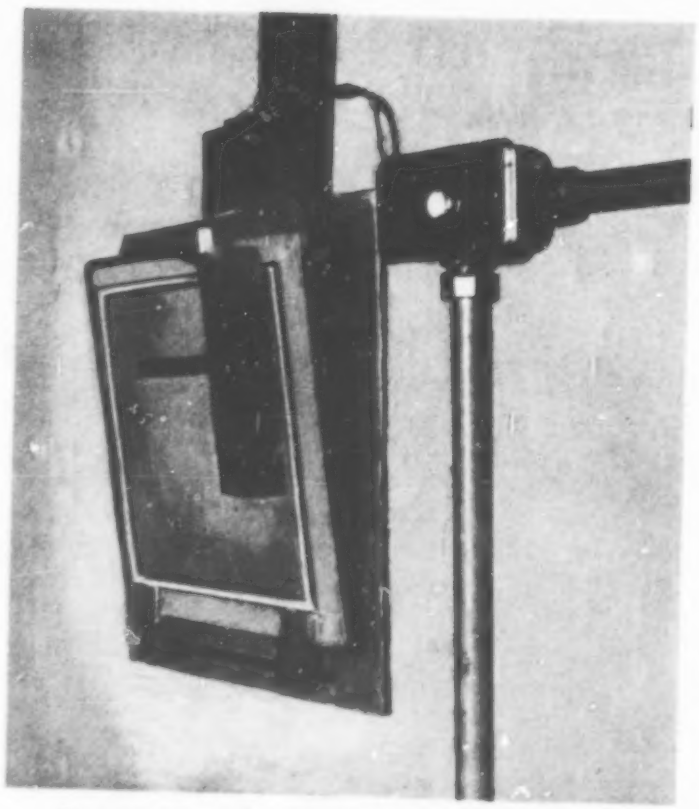


Figure 332. Typical chute door lock installation.

Stack Emissions

Data obtained from stack tests on a typical flue-fed incinerator modified with a draft control damper and roof afterburner are given in Table 122. Data obtained from the test designated in the table as C-546 also give emissions of aldehydes as formaldehyde as 2 pounds per ton, emissions of organic acids as acetic acid as 2.1 pounds per ton, and emissions of nitrogen oxides as 7 pounds per ton.

Operation

The sequence of operations performed in using a flue-fed incinerator, modified as discussed herein, starts with the locking of the chute doors from the main switch in the basement. The draft control damper is closed and the afterburner ignited by remote control from another switch also located in the basement.

The refuse is then ignited and, if the refuse is moist, the grate burners are also lighted. The refuse may be stoked frequently to uncover fresh material without fear of creating excessive fly ash emissions because of the draft-limiting action of the damper.

When the refuse has been destroyed, the grate burners are turned off and the grates are cleaned by dumping the ashes into the ash pit. After a brief period of time is allowed, to permit smoke from the smoldering ashes to clear, the afterburner is turned off and the draft control damper opened.

The final step, that of unlocking the chute doors, should not be performed until about 10 minutes after the grates have been cleaned. This delay allows

Table 122. PARTICULATE EMISSIONS FROM A TYPICAL FLUE-FED INCINERATOR MODIFIED WITH A DRAFT CONTROL DAMPER AND A ROOF AFTERBURNER

Test designation	Burning rate, lb/hr	Particulate matter			Afterburner efficiency %	Average oxygen content, %	Average stack volume, scfm	Average outlet temperature, °F
		lb/ton	gr/scf at 12% CO_2	gr/scf				
C-586-A1	100	5.9	0.20	0.004	80	12.1	760	1,130
C-586-A2	80	5.2	0.18	0.035	82	11.6	690	1,240
C-586-A3	68	5.6	0.20	0.034	80	12.7	710	1,130
C-546	49	1.2	0.15	0.027	85	9.5	590	1,560

the incinerator to cool so that newly charged refuse is not ignited by the residual heat in the incinerator.

BASEMENT AFTERBURNER

A typical basement afterburner installation uses a damper located at the base of the stack to control excessive draft and burning rate, and an afterburner located directly above the damper to consume smoke and combustible gases. Cooling air is ducted from the basement and admitted into the flue just below the first-floor charging chute to lower the temperature of the flue gas, thereby protecting the low-duty refractory lining of the flue and preventing the chute doors from becoming excessively hot. Chute door locks are also used on this unit to prevent damage to the damper from the charging of refuse during the burning period.

Design Procedure

The solenoid chute door locks and the draft control damper described in the discussion of roof afterburners are equally applicable to a basement afterburner installation. When used in a basement afterburner, the draft control damper is positioned in the flue as closely as possible to the combustion chamber. If the damper in this location is allowed to swing downward into the combustion chamber to permit charging, its upward swing may be obstructed by the accumulated refuse. To overcome this problem, the damper must be hinged to permit it to swing upward and lie against the flue wall.

Design parameters

The parameters, such as retention time, temperature level, and so forth, employed in designing a basement afterburner are the same as those employed in designing afterburners for smokehouses, ovens, and so forth as given in the first part of Chapter 5. The following specific features not encountered in the design of industrial afterburners must be considered in designing a basement afterburner.

1. The burners themselves must be located so that they do not obstruct the fall of refuse through the flue. Relatively inexpensive atmospheric or venturi burners are used in this installation since they can be arranged to fire across the flue. While forced-draft burners may be used, their higher cost usually makes them impractical.

2. The shape of the flue cannot be modified to produce a desired gas velocity, induce turbulence, or promote flame coverage, as the combustion chamber of an industrial afterburner can. The desired flame contact and mixing are promoted in basement afterburners by the proper location of the orifices in the damper. This damper is designed with an orifice located directly below the mouth of each burner. This arrangement provides the necessary contact between the afterburner flames and the products of combustion.

It it also necessary to provide for the admission of outside air into the flue to lower the temperature of the gases leaving the afterburner. Cooling the flue gas to 500°F protects the low-duty refractory inner lining of the flue from deterioration and prevents the outer walls of the flue, including the chute doors, from becoming excessively hot.

This air is supplied from the basement through a duct installed through the first floor and is introduced into the flue just below the first-floor charging door. This arrangement is used to prevent flue gases from venting directly into the living area of the building if the flue becomes accidentally blocked. A uniform draft on the downstream side of the afterburner is maintained by a barometric damper placed in the duct's entrance. It also provides the advantage of closing if any unexpected back pressure occurs in the flue.

Typical installation

In the basement afterburner, as shown in Figure 333, the burners are mounted in a rectangular hole located in the flue a short distance above the basement combustion chamber. A steel frame inserted in the hole supports the flue and the components of the afterburner. The afterburner unit consists of four venturi burners equally spaced across the opening. The area of the opening not occupied by the burners is covered by a steel plate to prevent the entrance of dilution air. An adequate amount of secondary air is admitted through this plate by holes equally spaced around each burner. The burners are provided with a continuously operating pilot.

The draft control damper is located just below the burners. Four slots in the surface of the damper are located directly under each burner and as near as practicable to the wall in which the burners are mounted.

Because temperatures in the flue in the afterburner zone may be approximately 1,200°F or more, the flue tile lining has been replaced with firebrick. The firebrick extends from the damper, past the burners, and ends just below the first-floor chute door.

Cooling air is admitted to the flue above the afterburner zone through a duct fitted with a barometric damper.

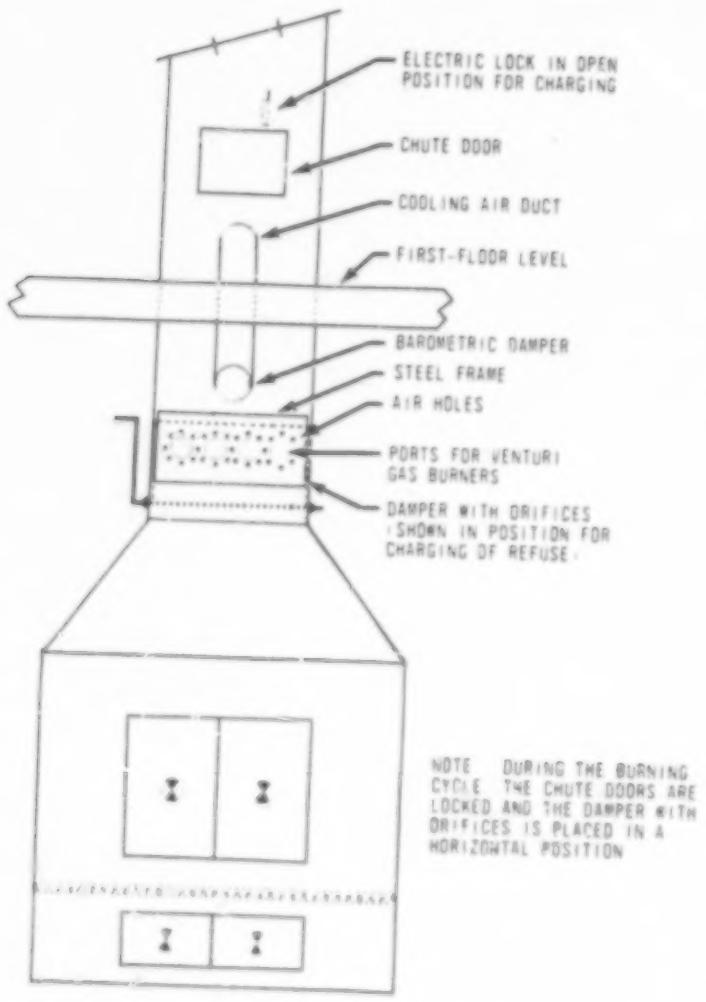

ELECTRIC LOCK IN OPEN POSITION FOR CHARGING
CHUTE DOOR
COOLING AIR DUCT
FIRST-FLOOR LEVEL
BAROMETRIC DAMPER
STEEL FRAME
AIR HOLES
PORTS FOR VENTURI GAS BURNERS
DAMPER WITH ORIFICES SHOWN IN POSITION FOR CHARGING OF REFUSE
NOTE DURING THE BURNING CYCLE THE CHUTE DOORS ARE LOCKED AND THE DAMPER WITH ORIFICES IS PLACED IN A HORIZONTAL POSITION

Figure 333. Flue-fed incinerator modified by an afterburner at the base of the flue.

Advantages

Compared with the roof afterburner, the basement afterburner has the advantages of shorter gas lines, a less expensive ignition system, and greater accessibility.

Disadvantages

The basement unit has the disadvantage of creating a hotter than normal flue, and may require expensive rebricking in the area near the afterburner.

Standards for Construction

The construction standards applicable to the draft control damper and chute door locks have been covered in the discussion of roof afterburners. Other standards are given in what follows.

Hot-zone refractory

The flue tile lining, which is usually a low-refractory-duty terra cotta, should be replaced with high-duty firebrick in the area between the hinged damper and the first-floor chute door. High-duty firebrick is recommended instead of lower duty firebrick or insulating firebrick because the refractory in this area must withstand both heat and compressive load.

Draft control damper

Since the orifices of the draft control damper are used to direct the combustion products from the refuse into the afterburner flames, the damper should be installed so as to minimize leakage around its edges. A small ledge approximately 1/2 inch wide is built into the refractory lining of the flue when the refractory is installed. The damper, when in place, rests against this ledge, preventing excessive leakage.

Stack Emissions

Emission data, in pounds per ton of refuse burned, obtained from tests on two typical flue-fed incinerators modified with basement afterburners and draft control dampers are presented in Table 123. Organic acids are reported as acetic acid, and aldehydes as formaldehyde.

Operation

The sequence of operation in using a flue-fed incinerator modified with a basement afterburner is the same as that described in the corresponding section under roof afterburners.

MULTIPLE-CHAMBER INCINERATOR, BASEMENT INSTALLATION

A flue-fed incinerator modified by the installation of a multiple-chamber incinerator in the basement includes the conversion of the combustion chamber of the flue-fed incinerator into a storage chamber for refuse. The refuse is manually transferred from storage to the multiple-chamber incinerator where it is burned. The products of combustion are ducted back into the flue above a sliding damper that seals off the refuse chamber, preventing uncontrolled dilution air leakage. As with other modifications, chute door locks are used to prevent the charging of refuse during the burning period.

Design Procedure

The second part of this chapter may be consulted for design procedures used for the multiple-chamber incinerator. Other design features embodied in the completed assembly follow.

1. The distance between the multiple-chamber incinerator and the storage bin should facilitate the transfer of rubbish.

Table 123. EMISSIONS FROM FLUE-FED INCINERATORS MODIFIED WITH A BASEMENT AFTERBURNER AND DRAFT CONTROL DAMPER

Test designation	Number of stories	Burning rate, lb/hr	Particulate matter			Organic acids, lb/ton	Nitrogen oxides, lb/ton	Aldehydes, lb/ton	Average stack volume, scfm	Average temperature at stack outlet, °F
			lb/ton	gr/scf at 12% CO_2	gr/scf					
C-619	4	32	6.1	0.22	0.011	5.2	16.0	3.1	970	640
C-822	6	104	6.5	0.23	0.028	5.9	4.2	1.8	1,400	450

2. As a further convenience in transferring the rubbish, the multiple-chamber incinerator should be constructed with the ignition chamber side close to the storage bin.

3. The multiple-chamber incinerator installed should be large enough to allow all the refuse normally collected per day to be consumed within 1 hour.

4. The draft provided for the multiple-chamber incinerator should be limited to its design value.

Draft control

The draft furnished for incinerators of the size commonly used in apartment houses, that is, incinerators burning between 50 and 250 pounds per hour, should not exceed approximately 0.20 inch of water column. Since the existing flue of the former single chamber is usually excessively high for the new installation, some provision for draft control must be furnished. A barometric damper, as shown in Figure 334, is installed at the end of the breeching between the multiple-chamber incinerator and the flue to maintain the correct draft.

Typical installation

The multiple-chamber installation is depicted in Figure 334. Conversion of the combustion chamber has been accomplished by removing the grates and smoothing the interior walls with plaster. To facilitate the removal of refuse for charging into the multiple-chamber incinerator, a large section of the front wall has been removed and replaced by a steel door. A breeching with a barometric damper has been installed from the top of the secondary combustion chamber of the multiple-chamber incinerator to the existing flue. A steel damper has been installed in the flue below the breeching to prevent dilution air from entering the flue through the refuse storage chamber.

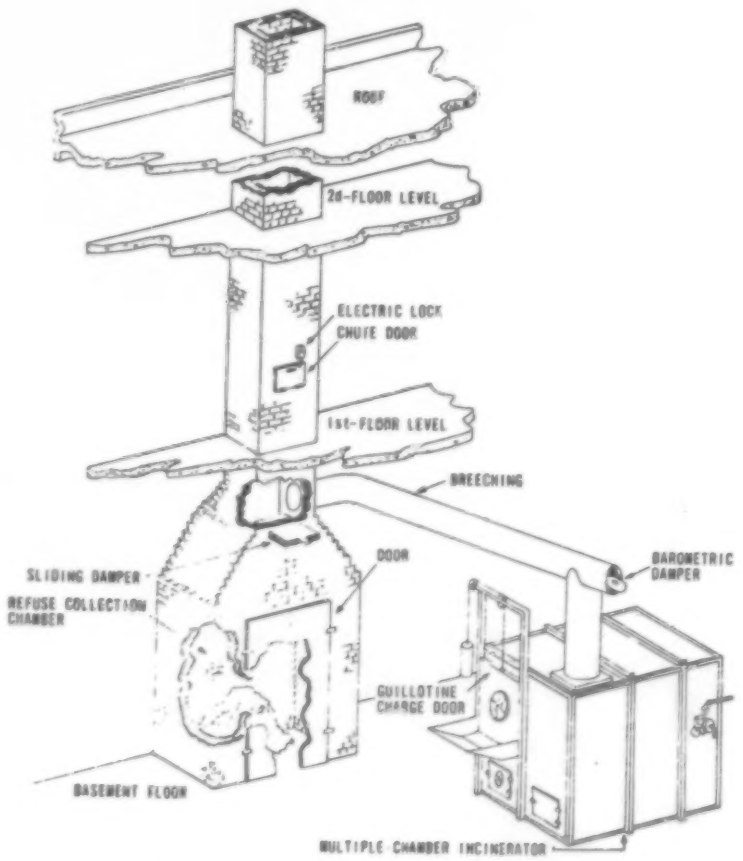


Figure 334. Flue-fed incinerator modified by the installation of a multiple-chamber incinerator (MacKnight et al., 1960).

Advantages

The multiple-chamber incinerator installation has two advantages relative to roof afterburners.

1. The cost of installation is lower as compared with that of a roof afterburner on buildings over 2 stories high. The first cost of a roof afterburner increases with building height because of the additional size, and length of gas line required.

2. It has no height limit. As explained in the section on draft control for roof afterburners, the height of a building on which an afterburner can be installed is limited by the amount of air leaking into the flue above the draft control damper.

The only advantage a multiple-chamber basement installation has relative to a basement afterburner is that the flue gases from the multiple-chamber installation are about 200°F cooler, than those from a basement afterburner. Because the flue linings and walls are correspondingly cooler, they are subjected to less thermal stress, and also are less likely to cause painful burns to apartment tenants.

Disadvantages

The multiple-chamber installation has the disadvantage of requiring hand transfer of all refuse from the storage bin into the multiple-chamber incinerator--a distasteful and time-consuming task. A second disadvantage is the amount of valuable basement space occupied by the multiple-chamber incinerator, which otherwise would be available for tenants' use.

Standards for Construction

Standards for constructing a multiple-chamber incinerator may be found in the second part of this chapter.

Stack Emissions

Emissions from typical flue-fed multiple-chamber installations are given in Table 124. Associated data have been included as a matter of interest.

Operation

Before burning is begun, the solenoid locks on the charging chute doors are actuated and the damper below the breeching is closed. The mixing chamber burners of the incinerator are then ignited. The ignition chamber burners are also ignited if the refuse is of low heating value or high moisture content. The charging and operation of the incinerator are as described in the second part of this chapter. Burning is usually carried out once a day, since the bin does not normally provide storage for much more than that length of time. When burning is completed, the incinerator burners are turned off, the doors to the bin are closed, the flue damper is opened, and the chute doors unlocked.

Illustrative Problem

Problem:

Calculate the size of a barometric damper to be installed in the breeching between a basement 100-pound-per-hour multiple-chamber incinerator and the flue to limit the draft for the multiple-chamber incinerator to 0.2 in. WC.

Given:

The flue is 18 inches square and has a cross-sectional area of 2.25 ft^2. The flue extends 92 feet above the breeching. The breeching itself is a 12-inch-diameter, insulated, straight duct 10 feet long.

Solution:

1. Compute the theoretical draft in the breeching at various average gas temperatures:

$$D_t = 0.52\ PH\ (\frac{1}{T_o} - \frac{1}{T_a})^*$$

*Kent, 1938.

Table 124. EMISSIONS FROM MULTIPLE-CHAMBER INCINERATOR, BASEMENT INSTALLATION

Test No.	Number of stories	Size of incinerator, lb/hr	Burning rate during test, lb/hr	Particulate matter		Emissions, lb per ton of refuse burned					Avg stack vol, scfm	Temp at top floor chute door, °F	Draft at ignition chamber, in. WC	Dia of barometric damper, in.	Airflow through barometric damper, scfm
				gr/scf at 12% CO_2	gr/scf	Particulate matter	Organic acids as acetic acid	Nitrogen oxides	Aldehydes as formaldehyde	Hydrocarbons as hexane					
C-511	4	100	65	0.2	0.016	1.7	1.2	0.8	0.14	0.14	860	310	Maximum 0.04	12	262
C-514	4	50	38	0.2	0.035	8.4	10.5	2.3	0.47	3.16	510	310	Maximum 0.06[a]	10	None
C-515	5	100	77	0.3	0.023	5.2	1.0	3.1	0.52	3.10	1,600	310	Maximum 0.03[b]	12	Not recorded
C-513	11	250	217	0.5	0.020	4.3	2.6	1.7	0.37	No data	2,700	230	Not recorded	14[c]	Not recorded
C-512	11	150	140	0.3	0.016	4.5	4.3	2.8	0.85	4.20	2,300	190	Maximum 0.09	14[c]	Estimate 900

[a] A 1/2-in. x 20-in. air leak around sliding damper.
[b] Air leaks around sliding damper.
[c] Two barometric dampers installed.

where:

D_t = theoretical draft, in. WC

P = barometric pressure, psi

H = height of flue above breeching, ft

T_o = ambient temperature, degrees Rankine

T_a = average stack temperature, degrees Rankine.

For an average flue gas temperature of 100°F:

$$D_t = (0.52)(14.7)(92)\left(\frac{1}{520} - \frac{1}{560}\right) = 0.092 \text{ in. WC}$$

Theoretical draft (calculated by the same formula) versus temperature is given in the following tabulation:

Temp, °F	D_t, in. WC	Temp, °F	D_t, in. WC
100	0.09	400	0.53
200	0.29	500	0.62
300	0.43	600	0.69

2. Compute the weight of air that must enter through the barometric damper to cool the products of combustion from the multiple-chamber incinerator to 300°F, heat losses being neglected:

Although neglecting losses causes the damper to be somewhat oversized, the draft can still be regulated with the weights on the damper. With the damper undersized, however, the draft cannot always be controlled.

$$(W_A)(C_{p2})(T_2 - T_A) = (W_{pc})(C_{p1})(T_1 - T_2)$$

where:

W_A = weight of air entering through barometric damper, lb/sec

W_{pc} = weight of flue gases, lb/sec

C_{p1} = average specific heat of products of combustion from multiple-chamber incinerator over temperature range of T_1 to T_2, Btu/lb-°F

C_{p2} = average specific heat of air over temperature range T_2 to T_A, Btu/lb-°F

T_2 = final temperature of flue gases, °F

T_1 = average temperature of gases from multiple-chamber incinerator, °F

T_A = temperature of air, °F.

From the illustrative problem in the second part of this chapter, the products of combustion leave the multiple-chamber incinerator at the rate of 0.517 lb/sec, the temperature is 990°F, and the specific heat is 0.26 Btu/lb-°F. The specific heat of air is 0.24 Btu/lb-°F.

$$(W_A \text{ lb/sec})(0.24 \text{ Btu/lb-°F})(300°F - 60°F) =$$

$$(0.517 \text{ lb/sec})(0.26 \text{ Btu/lb-°F})(990°F - 300°F)$$

$$W_A = 1.61 \text{ lb/sec}$$

3. Volume of air entering through the barometric damper:

$$\text{Volume (300°F)} = \frac{(1.61 \text{ lb/sec})(379 \text{ ft}^3/\text{mol})(760°R)}{(29 \text{ lb/mol})(520°R)}$$

$$= 30.8 \text{ cfs}$$

4. Volume of products of combustion from the multiple-chamber incinerator at 300°F:

From the illustrative problem in the second part of this chapter, the volume of products of combustion is 6.8 cfs at 60°F.

$$\text{Volume (300°)} = \frac{(6.8 \text{ cfs})(760°R)}{520°R}$$

$$= 9.93 \text{ cfs}$$

5. Total volume flowing through the breeching and flue at 300°F:

$$\text{Total volume (300°F)} = 30.8 \text{ cfs} + 9.93 \text{ cfs}$$

$$= 40.73 \text{ cfs}$$

6. Velocity through the breeching:

$$\text{Area of breeching} = 0.785 \text{ ft}^2$$

$$\text{Velocity (300°F)} = \frac{40.73 \text{ cfs}}{0.785 \text{ ft}^2} = 51.9 \text{ fps}$$

7. Friction loss in the breeching:

$$F_B = \frac{0.008\,(H)(V)^2}{(D)(T)}*$$

*Griswold, 1946.

where:

F_B = friction loss, in. WC

H = length of breeching, ft

V = velocity, fps

D = duct diameter, ft

T = temperature, degrees Rankine.

$$F_B = \frac{(0.008)(10)(51.9)^2}{(1)(760)} = 0.283 \text{ in. WC}$$

8. Velocity through the flue:

Area of flue = 2.25 ft^2

$$\text{Velocity (300°F)} = \frac{40.73 \text{ cfs}}{2.25 \text{ ft}^2} = 18.3 \text{ fps}$$

9. Friction loss in the flue:

$$F_F = \frac{0.002(H)(V)^2}{(m)(T)}^*$$

where:

F_F = friction loss, in. WC

H = height of flue above breeching, ft

V = velocity, fps

m = hydraulic radius, ft

T = temperature, degrees Rankine.

For rectangular cross section, the hydraulic radius is:

$$m = \frac{\text{area}}{\text{wetted perimeter}}$$

For the given flue, the hydraulic radius is:

$$m = \frac{(2.25 \text{ ft}^2)(12 \text{ in./ft})}{(4)(18 \text{ in.})} = 0.375 \text{ ft}$$

$$F_F = \frac{(0.002)(92)(18.3)^2}{(0.375)(760)} = 0.216 \text{ in. WC.}$$

10. Total friction losses in breeching and flue:

Total friction losses = 0.283 in. WC + 0.216 in. WC

= 0.499 in. WC

*Griswold, 1946.

11. Frictional losses (calculated by the same method) for assumed flue gas temperatures of 400° and 500°F are given in the following tabulation:

Temp, °F	Friction loss, in. WC
400	0.28
500	0.18

12. Determine the flue gas temperature:

A flue gas temperature of 380°F, representing a difference of 0.2 in. WC between the theoretical draft and the frictional losses, is obtained from a plot of the data derived herein, as shown in Figure 335.

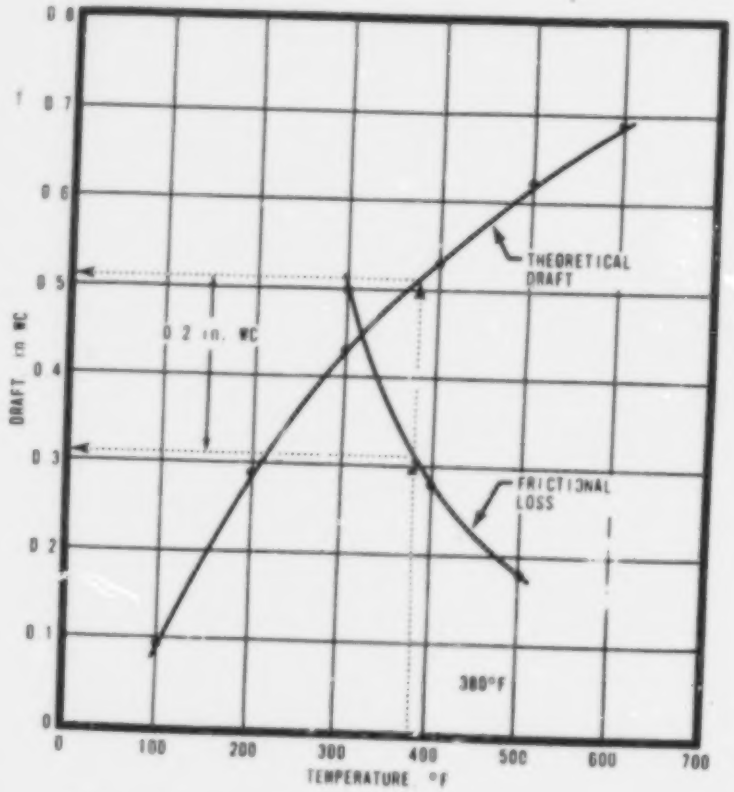


Figure 335. Draft at breeching of a multiple-chamber basement installation versus average flue gas temperature.

13. Weight of air entering through the barometric damper at 375°F:

$$(W_A)(C_{p2})(T_2 - T_A) = (W_{pc})(C_{p1})(T_1 - T_2)$$

where:

W_A = weight of air entering through barometric damper, lb/sec

W_{pc} = weight of flue gases, lb/sec

C_{p1} = average specific heat of products of combustion from multiple-chamber incinerator over temperature range of T_1 to T_2, Btu/lb-°F

C_{p2} = average specific heat of air over temperature range T_2 to T_A, Btu/lb-°F

T_2 = final temperature of flue gases, °F

T_1 = average temperature of gases from multiple-chamber incinerator, °F

T_A = temperature of air, °F.

$(W_A \text{ lb/sec})(0.24 \text{ Btu/lb-°F})(380°F - 60°F) =$

$(0.517 \text{ lb/sec})(0.26 \text{ Btu/lb-°F})(990°F - 380°F)$

$$W_A = 1.07 \text{ lb/sec}$$

14. Volume of air entering through the barometric damper:

Volume (60°F) =

$$\frac{(1.07 \text{ lb/sec})(60 \text{ sec/min})(379 \text{ ft}^3\text{/mol})}{29 \text{ lb/mol}} = 840 \text{ cfm}$$

15. Area of barometric damper:

The effective open area of a barometric damper is about 70 percent of its cross-sectional area. The area based on the calculated amount of air to be inspirated must, therefore, be increased accordingly.

From Table D8, Appendix D, one velocity head at 0.2 in. WC and 60°F is 1,780 fpm.

$$\text{Area} = \frac{(840 \text{ cfm})(144 \text{ in.}^2\text{/ft}^2)}{(1,780 \text{ fpm})(0.70)} = 97 \text{ in.}^2$$

16. Diameter of barometric damper:

$$\text{Area} = \frac{(\pi)(\text{Diameter})^2}{4}$$

$$\text{Diameter} = \left[\frac{(4)(97)}{3.14}\right]^{1/2} = 12 \text{ in. (sized to the nearest inch)}$$

PATHOLOGICAL-WASTE INCINERATORS

Pathological waste is defined to include all, or parts of, organs, bones, muscles, other tissues, and organic wastes of human or animal origin. This section is limited to those incinerators used for the burning of pathological wastes and to crematory furnaces that have design standards similar to those of pathological waste incinerators.

Chemically, pathological waste is composed principally of carbon, hydrogen, and oxygen. Slight amounts of many minerals, along with a trace of nitrogen, are also present. Physically, this waste consists of cellular structured materials and fluids. Each cell contains water, along with the elements and compounds forming the cell. The cells comprise the hair, fatty tissue, proteinaceous tissue, and bone in proportions varying with different animals. Blood and various other fluids in the organs are almost completely water.

The average chemical composition of whole animals, except for the proportion of water present, is very similar in all animals. The proportion of water present, compared with the total weight of the animals, varies widely among different animals, and among various conditions of freshness or decomposition of the animal material. Average chemical properties of pathological waste and combustion data are given in Table 125. These combustion data have been found to provide good results when used in design calculations for pathological-waste incinerators. The cremation of human remains differs from other pathological incineration only in that the body is usually contained in a wood-

Table 125. CHEMICAL COMPOSITION OF PATHOLOGICAL WASTE AND COMBUSTION DATA

Ultimate analysis (whole dead animal)		
Constituent	As charged	Ash-free combustible
	% by weight	% by weight
Carbon	14.7	50.80
Hydrogen	2.7	9.35
Oxygen	11.5	39.85
Water	62.1	-
Nitrogen	Trace	-
Mineral (ash)	9	-
Dry combustible empirical formula - $C_5H_{10}O_3$		

Combustion data (based on 1 lb of dry ash-free combustible)			
Constituent		Quantity	Volume
		lb	scf
Theoretical air		7.028	92.40
40% sat at 60°F		7.059	93
Flue gas with theoretical air 40% saturated	CO_2	1.858	16.06
	N_2	5.402	73.24
	H_2O formed	0.763	15.99
	H_2O air	0.031	0.63
Products of combustion total		8.054	105.92
Gross heat of combustion		8,820 Btu per lb	

en casket. The casket must be considered when designing these units and is usually assumed, for design calculations, to weigh 75 pounds and to have the chemical analyses and combustion properties of average wood given in Table 118.

THE AIR POLLUTION PROBLEM

Pathological-waste incinerators can produce emissions of fly ash smoke, gases, and odors that would be highly objectionable. Fly ash emission is usually inconsequential in this type of incinerator, but odor emissions may be very great. Visible smoke from this type of incinerator is highly repugnant on esthetic grounds to most people and is especially undesirable from crematory furnaces.

Poorly designed incinerators, with inadequate mixing, temperatures, and residence times emit highly objectionable air contaminants. Table 126 presents emission values measured for two separate multiple-chamber pathological-waste incinerators operating without secondary burners. These data show emissions that are similar to a single chamber design without a secondary chamber or afterburner.

AIR POLLUTION CONTROL EQUIPMENT

The prevention of air contaminant emissions by good equipment design is the best air pollution control procedure to follow. Inadequate equipment may be compensated for by use of an afterburner designed according to precepts set forth in the first part of this chapter. New equipment employing good design concepts can produce maximum combustion of pathological-waste material with a minimum of air contaminant emissions.

Design Procedure

A principal consideration in the design of pathological-waste incinerators is provision for the release of fluids as the material is destroyed. These

Table 126. EMISSIONS FROM TWO PATHOLOGICAL-WASTE INCINERATORS WITHOUT SECONDARY BURNERS (SOURCE TESTS OF TWO PATHOLOGICAL-WASTE INCINERATORS)

Test No.	549	563
	Mixing chamber burner not operating	Mixing chamber burner not operating
Rate of destruction to powdery ash, lb/hr	26.4	107
Type of waste	Placental tissue in newspaper at 40°F	Dogs freshly killed
Combustion contaminants,		
gr/scf[a] at 12% CO_2	0.500	0.300
gr/scf	0.017	0.128
lb/hr	0.030	0.430
lb/ton charged	2.270	8.040
Organic acids,		
gr/scf	0.010	0.034
lb/hr	0.020	0.110
lb/ton charged	1.514	2.050
Aldehydes,		
gr/scf	0.007	0.010
lb/hr	0.013	0.033
lb/ton charged	0.985	0.617
Nitrogen oxides,		
ppm	14.700	95
lb/hr	0.016	0.082
lb/ton charged	1.210	1.550
Hydrocarbons	Nil	Nil

[a] CO_2 from burning of waste only used to convert to basis of 12% CO_2. See Rule 53b, incinerators, in Appendix A.

fluids are frequently released in such quantities that they do not immediately evaporate and, hence, require the use of a solid hearth rather than grates in the ignition chamber. Pathological waste cannot be considered as forming a fuel bed when being incinerated, and the passage of air through the burning material is not a requirement in these units.

The presence of a relatively high percentage of moisture throughout each individual cell comprising the pathological waste presents a difficult evaporation problem. Evaporation of the moisture is necessary before the combustible animal tissue can be ignited. Moisture, however, evaporates only from those cells upon and near the surface of the material exposed to heat. Deeper lying tissue is almost completely insulated from the heat in the chamber and is heated only slowly. Evaporation of moisture from deeper cells cannot take place until the destruction of the cellular material above them causes them to be near the surface receiving heat. While the heat of combustion of the dry cellular material is considerable, the relatively small proportion of this material to the large amount of moisture present makes it ineffectual in initiating the evaporation processes. Auxiliary fuel must be burned to accomplish the necessary dehydration.

As with other incinerator design calculations, those for pathological-waste incinerators also fall into three general categories: (1) Combustion calculations, based upon the heat input of auxiliary fuel, the composition of waste, the assumed requirements for air, and heat losses; (2) flow calculations based upon the products of combustion and the expected gas temperatures; and (3) dimensional calculations based upon simple mensuration and empirical sizing equations. The factors to be used in these calculations for pathological incinerator design are given in Tables 127 and 128.

Simplifying assumptions may be made as follows:

1. The evaporation and burning rates, auxiliary-fuel burning rate, and average waste composition are taken as constant. Design parameters should be based upon that waste containing the highest percentage of moisture that may be expected to be destroyed in the unit.

2. The average temperature of the combustion products is determined through calculation of heat loss by using radiation and storage losses as determined in Table 129.

3. The overall average gas temperature should be about 1,500°F when calculations are based upon air for the combustible waste at 100 percent in excess of theoretical, and upon air for the primary burner at 20 percent in excess of theoretical. The minimum temperature of the gases leaving the ignition chamber should be 1,600°F.

4. Indraft velocity in the air ports is assumed to be at 0.1 inch water column velocity pressure (1,255 fpm).

5. The secondary air port is sized to provide 100 percent of the theoretical air for the combustible material in the waste charged.

Table 127. DESIGN FACTORS FOR PATHOLOGICAL IGNITION CHAMBER (INCINERATOR CAPACITY, 25 lb/hr TO 250 lb/hr)

Item	Recommended value	Allowable deviation, %
Hearth loading	10 lb/hr ft^2	± 10
Hearth length-to-width ratio	2	± 20
Primary burner design	$\frac{10 \text{ cf natural gas}}{\text{lb waste burned}}$	± 30
Arch height	See Figure 336	± 20
Gross heat release--ignition chamber	See Figure 336	± 20
Specific heat of the products of combustion including combustion of waste and natural gas	0.29 Btu/lb-°F	-

Table 128. GAS VELOCITIES AND DRAFT (PATHOLOGICAL INCINERATORS WITH HOT GAS PASSAGE BELOW A SOLID HEARTH)

Item	Recommended values	Allowable deviation, %
Gas velocities,		
Flame port at 1,600°F, fps	20	± 20
Mixing chamber at 1,600°F, fps	20	± 20
Port at bottom of mixing chamber at 1,550°F, fps	20	± 20
Chamber below hearth at 1,500°F, fps	10	± 100
Port at bottom of combustion chamber at 1,500°F, fps	20	± 20
Combustion chamber at 1,400°F, fps	5	± 100
Stack at 1,400°F, fps	20	± 25
Draft,		
Combustion chamber, in. WC	0.25[a]	- 0 + 25
Ignition chamber, in. WC	0.05 to 0.10	± 0

[a]Draft can be 0.20 in. WC for incinerators with a cold hearth.

A primary air port is not normally necessary in these units. Sufficient combustion air in the primary chamber is normally provided for both the fuel and waste material by the burner and by leakage at the charge door and other points in this chamber. When a primary air port is desired, its sizing should be based on the admission of 200 percent of the theoretical air necessary for the combustible waste material.

Table 129. HEAT LOSSES FROM IGNITION CHAMBER (STORAGE, CONVECTION, AND RADIATION LOSSES DURING INITIAL 90 MINUTES OF PATHOLOGICAL INCINERATION OPERATION)

Incinerator capacity, lb/hr	Loss expressed as % of gross heat input
25	36.3
50	32.8
100	29.75
200	25.3
250	23.6

The combustion calculations needed to determine weights and velocities of the products of combustion along with average temperatures may be derived from standard calculation procedures when the preceding assumptions are followed. The sizing requirements for inlet air areas are minimum; these areas should be oversized in practice to provide for operational latitude.

Ignition chamber

Dimensions of the ignition chamber are determined by deriving hearth loading and area, average arch height, and chamber volume from Figure 336 and from the factors given in Table 127. The input capacity of the ignition chamber burner is also determined from the factors given in Table 127.

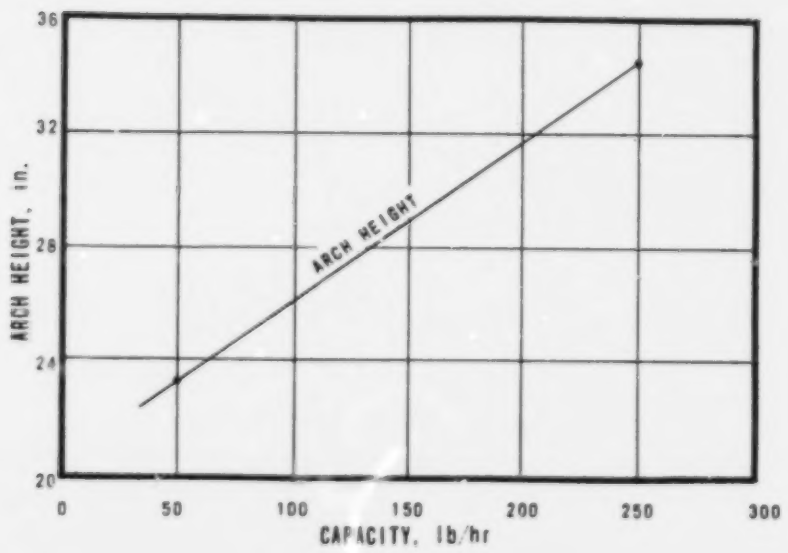


Figure 336. Arch height of pathological-waste ignition chamber.

Length-to-width ratios for the hearth are not critical. To provide for single-layer disposition of the material upon the hearth, however, with the resultant maximum exposure of the material to the burner flame pattern, a length-to-width ratio of 2 to 1 is most practical.

Secondary combustion zone

The velocity parameters stated in Table 128 are not too critical in these units. The relatively small amount of combustible material in the waste does not provide a problem too severe for achieving complete combustion. Particulate discharge from these incinerators has been found to be very light. The principal design consideration is an effective rate of destruction of the waste. Design consideration must, however, be given to one peculiar problem in the burning of this waste material: Whenever a deposit of fatty tissue or hair is exposed to flame or high-temperature gases, it quickly volatilizes. The sudden volatilization of these parts causes a flooding of gases and vapors that would be beyond the capacity of the secondary combustion zone designed on the basis of an average rate of operation. These periods of sudden volatilization then result in considerable amounts of unburned gases and vapors, which issue from the stack as dense, visible smoke.

Design of the secondary combustion zone for low-velocity gas movement at average volumes will provide for complete combustion, even during the periods of abnormally high combustion rates.

An auxiliary burner in the secondary combustion zone is necessary for these incinerators. This burner capacity need only be sufficient to maintain a 1,600°F temperature in the gases. To do this, the burner should be so located that the gases flowing from the ignition chamber can first mix with secondary air before passing through the flame of the secondary burner. Its location should also, however, be such that sufficient residence time of combustion gases is provided in the mixing chamber, after passage through the flame, for secondary combustion to occur.

Stack design

Calculations for stack design should be based upon a gas temperature of 1,400°F. Because design calculations are based upon an average rate of operation and because there will be periods when this rate will be exceeded, stack design velocity should be at or below 20 fps. Stack height should be determined so as to provide a minimum available draft of 0.20 inch water column at the breeching. This is an absolute minimum draft provision for all pathological-waste incinerators. When pas-

sage of hot gas beneath the hearth is to be provided, the minimum available stack draft at the breeching should be designed for 0.25 inch water column. This higher draft will compensate for the additional resistance to gas flow in its passage beneath the hot hearth.

Supplementary calculations

Piping requirements for the gas fuel supply line should be determined. This sizing should provide for supplying the total maximum capacity of the burners used in both the ignition and secondary combustion chambers.

Crematory design

The shape and size of the ignition chamber in crematory units is dictated by the dimensions of a casket. The same factors influencing the design of other pathological-waste units should, however, be used for all other parameters of the crematory ignition chamber. In calculating the volume and weight of products of combustion, consideration must be given to the admission of somewhat larger amounts of excess air when the design includes a charge door at one end and a cleanout door at the other end of the ignition chamber. Increasing the burner capacity in these installations may be necessary. Parameters for the secondary combustion zone of crematory furnaces will be based upon the same factors as those given for normal pathological-waste incinerators. The volume and weight of products of combustion will include those from the burning of the casket. These units cannot, however, be designed on the basis of assuming that the burning rate is constant. There will be some period of time during the total operation in which a higher rate of production of combustion products occurs. Table 130 sets forth two possible operating procedures with arbitrary but representative grouping of periods of operation that will produce varying combustion rates. The factors for the parameters of the secondary combustion zone should be used for the period of operation that produces the greatest flow of combustion products.

Incinerator design configuration

There are several possible configurations that might be used in the construction of pathological-waste incinerators. Several are illustrated in Figures 337, 338, and 339.

Table 130. OPERATING PROCEDURES FOR CREMATORY

Phase	Duration, 1-1/2 hr operation, min	Burner settings	Casket	Body		
				Moisture	Tissue	Bone Calcined
Charging[a]	-	Secondary zone on				
Ignition	15	All on	20% burns	-	-	-
Full combustion	30	All on	80% burns	20% evap	10% burns	-
Final combustion	45	All on	-	80% evap	90% burns	50%
Calcining	1 to 12 hr	All off (or small primary on)	-	-	-	50%
OR						
	Duration, 2-1/2 hr operation, min					
Ignition	15	All on	20% burns	-	-	-
Full combustion	30	Primary off	60% burns	20% evap	-	-
Final combustion	15	All on	20% burns	20% evap	20% burns	50%
	90	All on	-	60% evap	80% burns	-
Calcining	1 to 12 hr	All off (small primary may be on)				

[a]Charge: Casket 75 lb wood
Body 180 lb
Moisture - 108 lb
Tissue - 50 lb
Bone - 22 lb

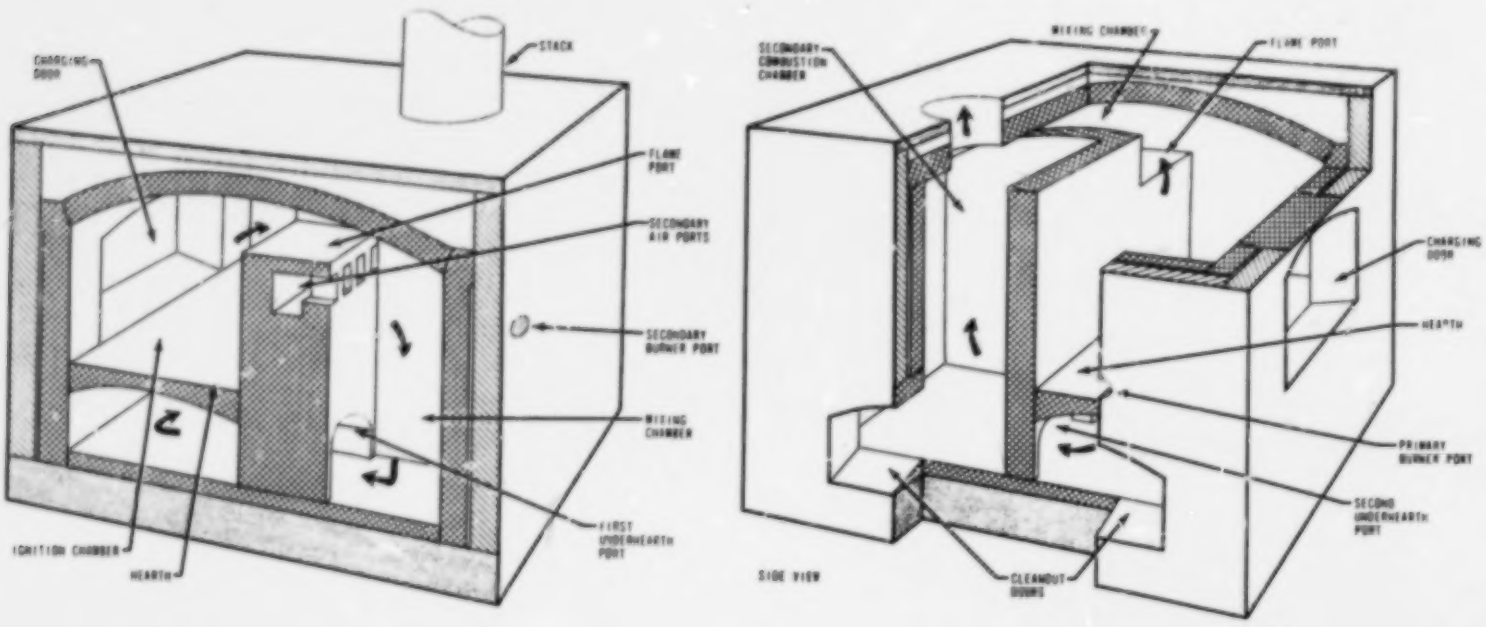


Figure 337. Multiple-chamber pathological-waste incinerator.

Illustrated in Figure 337 is an adaptation of the design for the retort-type multiple-chamber incinerator for destruction of pathological waste. In this adaptation, three configuration differences from the comparable unit illustrated in Figure 308 are immediately visible:

1. The use of a solid hearth instead of grates;

2. the provision for heating the hearth by passing the products of combustion from the mixing chamber through a chamber beneath the hearth before they exit to the combustion chamber, permitting both transfer of heat to the unexposed portions of the material lying on the hearth, and more rapid evaporation of fluids that spill upon the hearth or seep through it; and

3. the use of a side charging door.

Individual components in pathological waste are frequently large. In addition, the charge must be disposed over the hearth in a single layer of components to provide for maximum exposure of surface area to the burner flame. These two factors make necessary the designing of the charge opening with width and height dimensions close to the maximum dimensions of the ignition chamber. The side charging door will not, as with the incineration of general refuse, cause the emission of excessive particulate matter from these incinerators.

Figure 338 illustrates a retort for the burning of pathological waste added to a standard multiple-chamber incinerator. When these retorts are used, the gases from the retort should pass across the rear of the ignition chamber of the standard incinerator. The design of the retort incorporates the factors given for the design of the ignition chamber of a pathological-waste incinerator. The design of the remainder of the combination incinerator is only slightly influenced by the addition of this retort under most circumstances. This design concept may be used only where the pathological-waste load occurs periodically and in small amounts.

Figure 339 illustrates a human crematory retort. This illustration is but one design, and many variations are found. Characteristically, these retorts provide for a flame along the length of a shallow, narrow, long charging chamber. The design illustrated employs a "hot hearth." Other designs provide for flame passage on all sides of the charge including the underside. The hot hearth principle is not always employed in crematory retorts. The unit illustrated was not originally designed with secondary burners; these burners were added in the gas passageway below from the primary ignition chamber at a later date to eliminate smoke.

Standards for Construction

The general discussions for the construction of multiple-chamber incinerators given in previous parts of this chapter cover most of the problems found in constructing pathological-waste incinerators. The use of extra-high-grade refractories (super-duty fire brick or its equivalent plastic or castable refractory) in these units is imperative. Hearth construction must provide physical strength at elevated temperature to sustain the maximum loading possible. Characteristically, in patho-

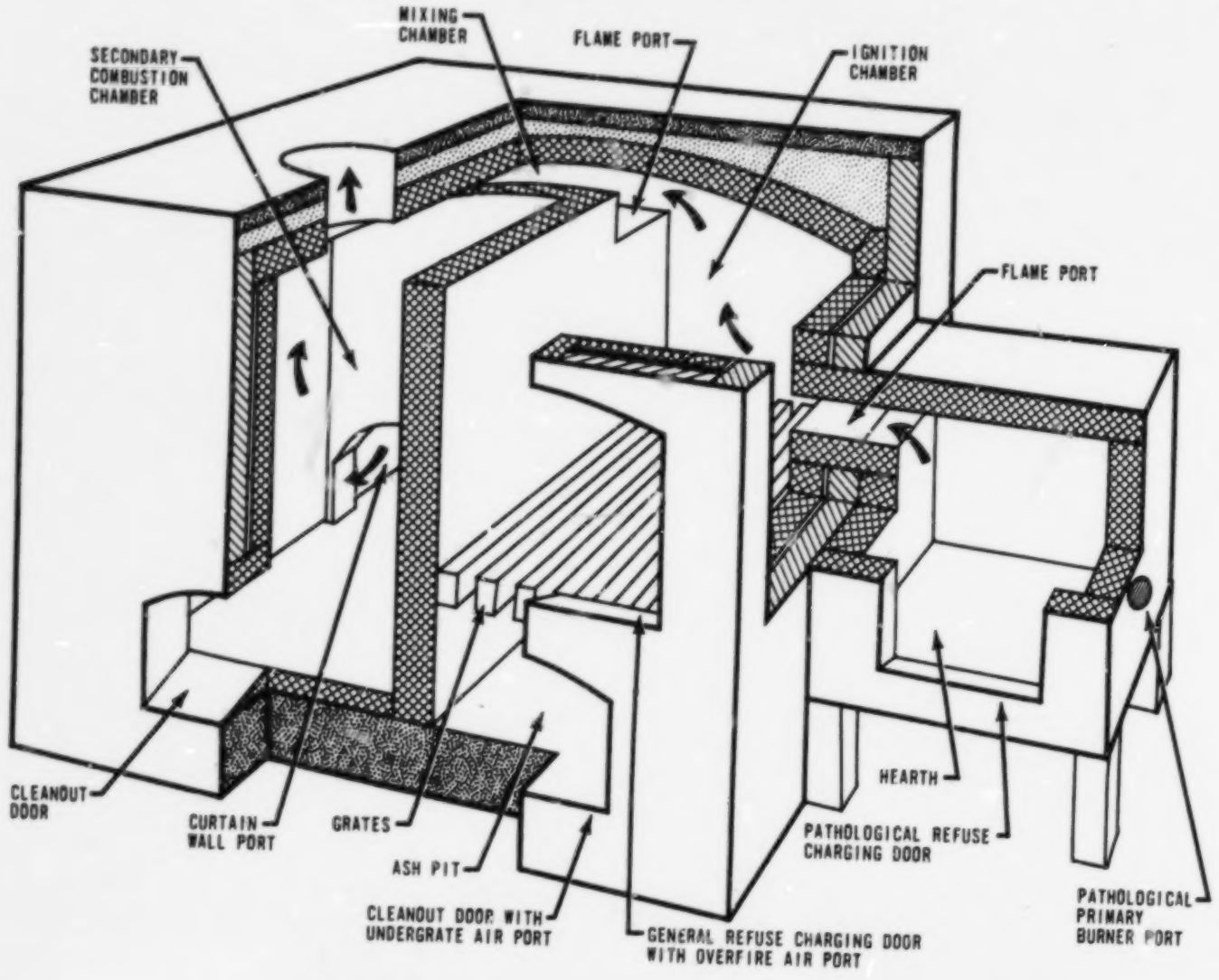


Figure 338. Multiple-chamber incinerator with a pathological-waste retort.

logical-waste incinerators, the initial charge of material on the hearth can have a total weight in excess of the hourly capacity of the unit. When making calculations for the strength of the hearth, calculate the hearth loading at twice the combustion rate, or more.

Stack Emissions

Visual emissions of fly ash are not evident from pathological-waste incinerators. Air contaminants, as solid, liquid, and gaseous emissions, determined for two typical units, are given in Table 131.

Operation

Operation of pathological-waste incinerators is, in general, more simple than that for other types of refuse incinerators. Preheating the secondary combustion zone before charging and operating these units is good practice. The primary burner or burners should not be ignited until charging has been completed and the charge door closed. The material to be destroyed should be disposed on the hearth in a manner that provides for maximum exposure to the flame of the primary burner. Further overcharging the unit by placing one component of the charge on top of another is not good practice. Care should be exercised to ensure that the primary burner port is not blocked by any element of the charge.

When the amount of material to be destroyed exceeds what can be normally charged, stoking and additional charging should be practiced only after considerable reduction of the initial charge has occurred. The primary burner should be shut off before the charge door is opened and stoking or additional charging takes place. Before an additional charge is made, the material remaining on the hearth should be gently pushed towards the end of the hearth nearest the flame port. The fresh charge should then be disposed on the exposed

hearth toward the primary burner. When recharging is complete, the charge door should first be closed before the primary burner is once again ignited.

Air port adjustment normally has only a minor role in the regulation of the operation of these incinerators. Making further adjustments to the secondary air port after it has been adjusted to provide proper operation under normal burning conditions is usually not necessary. The only operating difficulty to be encountered occurs when large deposits of fatty tissue or hair are exposed to the burner flame. As previously stated, the sudden volatilization of this material occasions a sudden rush of gases and vapors into the secondary chamber. On these occasions some black smoke may issue from the stack. This surge of gas volume, if very large, could even result in pressurizing the ignition chamber, causing smoke to be forced out around the charge door. Operational control, when this occurs, is obtained by reducing the burner rate in the ignition chamber. Under exceptional conditions, shutting this burner off for a few minutes may even be necessary. White

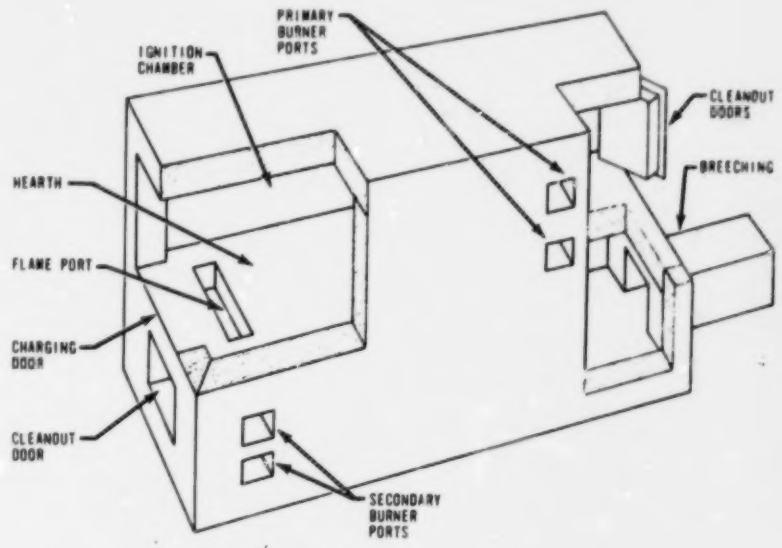


Figure 339. Crematory retort.

Table 131. EMISSIONS FROM TWO PATHOLOGICAL-WASTE INCINERATORS WITH SECONDARY BURNERS

Test No.	549	563
	Mixing chamber burner Operating	Mixing chamber burner Operating
Rate of destruction to powdery ash, lb/hr	19.2	99
Type of waste	Placental tissue in newspaper at 40°F	Dogs freshly killed
Combustion contaminants, gr/scf[a] at 12% CO_2	0.200	0.300
gr/scf	0.014	0.936
lb/hr	0.030	0.360
lb/ton charged	3.120	7.260
Organic acids, gr/scf	0.006	0.013
lb/hr	0.010	0.050
lb/ton charged	1.040	1.010
Aldehydes, gr/scf	N.A.[b]	0.006
lb/hr	N.A.[b]	0.020
lb/ton charged	N.A.[b]	0.400
Nitrogen oxides, ppm	42.70	131
lb/hr	0.08	0.[illegible]9
lb/ton charged	8.84	2
Hydrocarbons	Nil	Nil

[a] CO_2 from burning of waste used only to convert to basis of 12% CO_2. See Rule 53b, incinerators, in Appendix A.
[b] Not available.

smoke issuing from the stack usually indicates that air is entering the unit in an amount exceeding the ability of the burners to heat sufficiently. This is best overcome by increasing secondary or primary burner fuel rates. Very rarely is it necessary to adjust the secondary air port to lower the admission of air when white smoke persists.

Automatic temperature control may be used to operate these units. Temperature control should be achieved by using the primary burner only. The secondary burner should not be shut off or modulated to a lower operating rate by these controls. The temperature-sensing element may be placed in the combustion chamber, breeching, or stack. Precise temperature control at any of these points is then achieved by modulating or shutting off the primary burner. This operation to control temperatures does not affect the emission of air contaminants. When temperature control is attempted by control of the secondary burner, provision of the response desired will be found difficult, and the emissions of air contaminants will be increased when the burner's rate of fire is reduced or shut off by control action.

There is no burndown period in the operation of pathological-waste incinerators. The degree of destruction desired for the waste material dictates the length of time the primary burner is left in operation. Some operations are normally ceased when the material has been reduced to clean, white bone. When reduction of the bone to powdery ash is desired, the primary burners are continued in operation until this is achieved. After the shutoff of the primary burner, the secondary burner should not be shut off until smoldering from the residual material on the hearth in the primary chamber has ceased.

The hearth should be frequently cleaned to prevent buildup of ash residue and slag-like deposits. Frequency of cleanout of the combustion or settling chamber depends upon incinerator use. Deposits in this chamber should be removed to avoid re-entrainment in the exhaust gases.

Illustrative Problem

Problem:

Design an incinerator to dispose of 100 pounds of dog bodies per hour.

Design:

Select a multiple-chamber retort-type incinerator with a hot-gas passage below a solid hearth.

Solution:

1. Design features of ignition chamber:

   From Table 127, hearth loading is 10 lb/hr per ft^2.

   Hearth area

   $(100\ lb/hr) \div (10\ lb/hr\text{-}ft^2) = 10\ ft^2$

   Hearth dimensions

   Length-to-width ratio = 2

   Let w = width of hearth in ft

   $(w)(2w)$ = hearth area

   $2w^2 = 10\ ft^2$

   $w = 2.24$ ft

   Length $= 2w = 4.48$ ft

   From Figure 336, arch height = 25.8 in.

   Total ignition chamber volume $= 21.5\ ft^3$

2. Capacity of primary burner:

   From Table 127, primary burner consumption is 10 scf natural gas per lb waste burned.

   $$\left(\frac{10\ \text{scf natural gas}}{\text{lb waste burned}}\right)\left(\frac{100\ \text{lb}}{\text{hr}}\right) = 1,000\ \text{cfh}$$

3. Composition by weight of refuse:

Dry combustibles	(100 lb/hr)(0.29) =	29 lb/hr
Contained moisture	(100 lb/hr)(0.62) =	62 lb/hr
Ash	(100 lb/hr)(0.09) =	9 lb/hr
Total		100 lb/hr

4. Gross heat input:

   From Table 125, the gross heating value of waste is 8,820 Btu/lb and from Table D7 in Appendix D, the gross heating value of natural gas is 1,100 Btu/scf.

   Waste
   $(29\ lb/hr)(8,820\ Btu/lb) = 256,000$ Btu/hr

   Natural gas
   $(1,000\ cfh)(1,100\ Btu/scf) = 1,100,000$ Btu/hr

   Total 1,356,000 Btu/hr

5. Heat losses:

(a) From Table 129, gross heat losses by storage, conduction, and radiation are 29.75% of gross heat input.

(0.2975)(1,356,000 Btu/hr) = 404,000 Btu/hr

(b) Evaporation of contained moisture at 60°F

The heat of vaporization of water at 60°F is 1,060 Btu/lb

(62 lb/hr)(1,060 Btu/lb) = 65,700 Btu/hr

(c) Evaporation of water formed from combustion of waste at 60°F

From Table 125, combustion of 1 lb of waste yields 0.763 lb of water.

(0.763 lb/lb)(29 lb/hr)(1,060 Btu/lb) =

23,450 Btu/hr

(d) Evaporation of water formed from combustion of natural gas at 60°F

From Table D7, Appendix D, 0.099 lb of water is formed from combustion of 1 scf of natural gas.

$$\left(\frac{0.099 \text{ lb water}}{1 \text{ scf}}\right) (1,000 \text{ scfh})(1,060 \text{ Btu/lb})$$

= 105,000 Btu/hr

(e) Sensible heat in ash

Assume ash is equivalent in composition to calcium carbonate.

Average specific heat is 0.217 Btu/lb-°F

$$H = W_A (C_p)(T_2 - T_1)$$

where

H = sensible heat, Btu/hr

W_A = weight of ash, lb/hr

C_p = average specific heat of ash, Btu/lb-°F

T_2 = final temperature, °F

T_1 = initial temperature, °F

H = (9 lb/hr)(0.217 Btu/lb-°F)(1,600°F - 60°F)

= 3,000 Btu/hr

(f) Total heat losses

(a) + (b) + (c) + (d) + (e) = total heat losses

404,000 Btu/hr + 65,700 Btu/hr + 23,450 Btu/hr

105,000 Btu/hr + 3,000 Btu/hr = 601,150 Btu/hr

6. Net heat available to raise products of combustion:

Gross heat input - heat losses = net heat available

1,356,000 Btu/hr - 601,150 Btu/hr = 754,850 Btu/hr

7. Weight of products of combustion:

From Table 125, combustion of 1 lb waste with 100% excess air will yield 15.113 lb of combustion products.

From Table D7, Appendix D, combustion of 1 scf natural gas with 20% excess air will yield 0.999 lb of combustion products.

Waste (29 lb/hr)(15.133 lb/lb)	=	438 lb/hr
Contained moisture	=	62 lb/hr
Natural gas (1,000 cfh)(0.999 lb/scf)	=	999 lb/hr
Total weight of combustion products		1,499 lb/hr

8. Average gas temperature:

Assume the average specific heat of combustion products is 0.29 Btu/lb-°F

$$Q = (W)(C_p)(T_2 - T_1)$$

where

Q = net heat available, Btu/hr

W_c = weight of combustion products, lb/hr

C_p = average specific heat of combustion products, Btu/lb-°F

T_2 = average gas temperature, °F

T_1 = initial temperature, °F.

$$T_2 = T_1 + \frac{Q}{(W_c)(C_p)}$$

$$T_2 = 60 + \frac{754,850}{(1,499)(0.29)} = 1,740°F$$

This average temperature exceeds minimum design temperature of 1,600°F. The primary burner has, therefore, adequate capacity.

9. Secondary air port size:

Design secondary air port to supply theoretical air for combustion of waste.

Design secondary air port 100% oversize with a draft of 0.10 in. WC. From Table D8, Appendix D, 0.10 in. WC is 1,255 fpm.

From Table 125, 1 lb of waste requires 93 scf of air.

(29 lb/hr)(93 scf/lb) = 2,697 cfh
or 44.93 cfm
or 0.749 cfs

$$\frac{(44.93 \text{ cfm})(144 \text{ in.}^2/\text{ft}^2)}{1,255 \text{ fpm}} (2) = 10.3 \text{ in.}^2$$

10. Weight of maximum air through secondary port:

From Table D1, Appendix D, the density of air is 0.0763 lb/scf.

(2)(2,697 cfh)(0.0763 lb/scf) = 411.5 lb/hr

11. Heat required to raise maximum secondary air from 60° to 1,600°F:

From Table D4, Appendix D, 399.6 Btu is required to raise 1 lb air from 60° to 1,600°F.

(411.5 lb/hr)(399.6 Btu/lb) = 164,400 Btu/hr

12. Natural gas required by secondary burner:

Design for combustion of natural gas with 20% excess air. From Table D7, Appendix D, the calorific value of natural gas is 552.9 Btu/scf at 1,600°F.

(164,400 Btu/hr) ÷ (552.9 Btu/scf) = 298 cfh

13. Volume of products of combustion:

(a) Through flame port

From Table 125, combustion of 1 lb waste with 100% excess air will yield 198.92 scf of combustion products.

From Table D7, Appendix D, combustion of 1 scf natural gas with 20% excess air will yield 13.477 scf of combustion products.

Waste (29 lb/hr)(198.92 scf/lb) = 5,769 scfh

Water (62 lb/hr) $\frac{(379 \text{ scf/lb mole})}{18 \text{ lb/lb mole}}$ = 1,305 scfh

Natural gas (1,000 scfh)$\left(\frac{13.53 \text{ scf}}{\text{scf}}\right)$ = 13,530 scfh

Total volume of gases 20,604 scfh
or 344 scfm
or 5.75 scfs

(b) Through exit from mixing chamber

Design secondary burner for combustion at 20% excess air.

Products of combustion through flame port = 20,604 scfh

Products of combustion from secondary burner (298 cfh)(13.53 scf/scf) = 4,030 scfh

Maximum air through secondary air port (2)(2,697 scfh) = 5,394 scfh

30,028 scfh
or 500 scfm
or 8.33 scfs

14. Incinerator cross-sectional areas:

(a) Flame port area

Design flame port for 20 fps velocity at 1,600°F

$$\text{Area} = \frac{(5.75 \text{ scfs})(2,060°R)}{(20 \text{ fps})(520°R)} = 1.14 \text{ ft}^2$$

(b) Mixing chamber area

Design mixing chamber for 20 fps velocity at 1,600°F

$$\text{Area} = \frac{(8.33 \text{ scfs})(2,060°F)}{(20 \text{ fps})(520°R)} = 1.65 \text{ ft}^2$$

(c) Port area at bottom of mixing chamber

Design port for 20 fps velocity at 1,550°F

$$\text{Area} = \frac{(8.33 \text{ scfs})(2,010°R)}{(20 \text{ fps})(520°R)} = 1.61 \text{ ft}^2$$

(d) Chamber area beneath hearth

Design chamber for 10 fps velocity at 1,500°F

$$\text{Area} = \frac{(8.33\ \text{scfs})(1,960°\text{R})}{(10\ \text{fps})(520°\text{R})} = 3.14\ \text{ft}^2$$

(e) Port at bottom of combustion chamber

Design port for 20 fps velocity at 1,500°F

$$\text{Area} = \frac{(8.33\ \text{scfs})(1,960°\text{R})}{(20\ \text{fps})(520°\text{R})} = 1.57\ \text{ft}^2$$

(f) Combustion chamber

Design combustion chamber for 5 fps velocity at 1,400°F

$$\text{Area} = \frac{(8.33\ \text{scfs})(1,860°\text{R})}{(5\ \text{fps})(520°\text{R})} = 5.95\ \text{ft}^2$$

(g) Stack

Design stack for 20 fps velocity at 1,400°F

$$\text{Area} = \frac{(8.33\ \text{scfs})(1,860°\text{F})}{(20\ \text{fps})(520°\text{R})} = 1.49\ \text{ft}^2$$

15. Stack height:

Design stack for an effective draft of 0.25 in. WC in the combustion chamber. Assume friction losses are 12.5% of theoretical draft at 20 fps and 1,400 °F

Theoretical draft required

$$\frac{0.25\ \text{in. WC}}{1 - 0.125} = 0.286\ \text{in. WC}$$

Stack height

$$D_t = 0.42\ PH\left(\frac{1}{T} - \frac{1}{T_1}\right)^*$$

where

D_t = theoretical draft, in. WC

T = ambient air temperature, °R

T_1 = average stack gas temperature, °R

P = atmospheric pressure, lb/in.^{2}

H = stack height, ft

$$H = \frac{0.286}{(0.42)(14.7)\left(\frac{1}{520} - \frac{1}{1,860}\right)} = 33.4\ \text{ft}$$

*Kent, 1936.

DEBONDING OF BRAKE SHOES AND RECLAMATION OF ELECTRICAL EQUIPMENT WINDINGS

Brake shoe debonding and reclamation of electrical equipment windings are similar combustion processes, both using equipment nearly identical in design. These processes differ from incineration and other combustion reclamation processes in that the combustible contents of the charge are usually less than 10 percent by weight, and high temperatures must be avoided to prevent damaging the salvageable parts.

DEBONDING OF BRAKE SHOES

Bonded brake linings contain asbestos mixed with binders consisting of phenolic resins, synthetic rubber, or bodied oils such as dehydrated linseed oil. Carbon black, graphite, metallic lead, thin brass strips, and cashew nut shell oil added in small amounts act as friction-modifying agents (Kirk and Othmer, 1947). These materials are blended and extruded into curved lining to fit the brake shoe. The lining is then heated to produce a hard surface.

Adhesives for bonding the lining are composed mostly of rubber or phenolic resins. Small amounts of vinyl are sometimes combined with phenolic resins. The linings are originally bonded to steel shoes with adhesive, of a thickness of 0.008 to 0.01 inch, by subjecting them to pressure and a temperature of 400°F for a specific time to develop maximum bond strength.

In the brake-debonding process, brake shoes are charged to an oven, called a debonder, to which external heat is applied carefully to minimize warpage of the shoes. Adhesive portions of the lining start to melt, and destructive distillation begins at about 600°F (Kirk and Othmer, 1947). In the absence of flame, the melting of the adhesive proceeds until enough organic material is volatilized to initiate burning. At 800°F, thermal debonding results in the adhesive's being burned or charred. Burning continues at temperatures less than 1,000°F until all combustibles have been consumed. Once combustion has been initiated, the heating value of the adhesive is usually sufficient to maintain burning without external heat.

After the brake shoes are removed from the debonder, the brittle linings either fall from the shoes or are knocked loose by light tapping. Carbonized material adhering to the shoes is removed by abrasive blasting, and the clean shoes are ready for bonding with new linings.

RECLAMATION OF ELECTRICAL EQUIPMENT WINDING

A major portion of the reclamation of direct-current electrical equipment involves automotive starters and generators. An average-size starter or generator weighs 20 pounds and contains approximately 2 or 3 pounds of salvageable copper wire. Reclamation of alternating-current electrical equipment usually involves squirrel cage motors. Rotors removed from squirrel cage motors contain no organic material and, therefore, require no processing. The starters of these motors contain 5 to 10 percent combustible organic materials.

Table 132 gives the average composition and the amount of combustibles in major components of electrical equipment. While these data still hold true today, trends in new construction point to the use of greater quantities of noncombustible glass cloth in place of cambric. Acrylic resin, epoxy resin, silicone elastomers, and polyvinyl chloride are replacing cambric installation and varnish coatings.

In rebuilding electrical equipment and reclaiming copper windings, the insulation is burned from the windings of motors, generators, and transformers. After combustion is completed, the copper wire windings are separated and sold for scrap. Pole pieces, shafts, frames, and other parts are cleaned of char and rewound with new wire. During the reclamation process, combustible organic compounds used to insulate copper wire begin to volatilize upon application of heat. Ignition occurs above 600°F, and combustion is virtually completed at 900°F. Since the combustible contents of the charge are usually insufficient to sustain burning, auxiliary heat is usually supplied by primary burners during the complete operation. By restricting the combustion air, the burning insulation may provide over 50 percent of the total process heat requirements.

The temperature in the furnace is kept below 1,000°F to minimize warpage of metal parts and oxidation of the copper wire. The larger the individual item, the longer the preheat time, to prevent warping of the steel components. For example, a 100-hp motor requires a preheat time of over 1-1/2 hours.

THE AIR POLLUTION PROBLEM

The practice of reclaiming electrical windings and debonding brakeshoes by open burning or burning

Table 132. COMBUSTIBLE CONTENT OF ELECTRICAL EQUIPMENT

Components	Average wt % combustible	Combustible description
A-C industrial		
Motor and generators		
Casing	Nil	
Stator	5 to 10	Cambric and varnish
Squirrel cage rotor	Nil	
Wound rotor	5 to 10	Cambric and varnish
D-C industrial		
Motors and generators		
Casing	Nil	
Armature	5 to 10	Cambric and varnish
Field rings	5 to 7	Cambric and varnish, or acrylic resin, epoxy resin, silicones, PVC
Automotive		
Starters and generators		
Casing	Nil	
Armatures with shaft	1 to 2	Wood strips Fish paper
Generator field coils	5 to 10	Cambric and varnish
Starter field coils	5 to 10	Varnish Fish paper
Transformers		
Casing	Nil	
Windings	7 to 10	Cambric and varnish Oil[a]

[a]Oil-filled transformers only.

in a single-chamber device results in the emission of large quantities of smoke, odors, and other combustion contaminants. Emissions of air contaminants from these processes are summarized in Tables 133 and 134.

Table 133. STACK EMISSIONS FROM BRAKESHOE DEBONDING IN SINGLE CHAMBERS WITHOUT CONTROLS

Item	Test No.	
	C-606	C-651
Composition of charge	175 shoes	60 shoes
Charge weight, lb	265	--
Duration of test, min	38	8.75
Combustible content of charge, wt %	5	5
Stack gas flow rate, acfm	380	150
Average gas temperature, °F	200	600
Particulate matter, gr/scf at 12% CO_2	2.6	0.5
Particulate matter, lb/hr	0.70	0.75
Sulfur dioxide, lb/hr	0.24	a
Carbon monoxide, lb/hr	0.54	0
Organic acids as acetic acid, lb/hr	0.22	a
Aldehydes as formaldehyde, lb/hr	0.10	a
Nitrogen oxides as NO_2, lb/hr	0.02	a
Hydrocarbons as hexane, lb/hr	0.05	a
Smoke emissions, opacity range Ringelmann chart	0 to 80% brown-white	0 to 10% b...

[a]Not sampled.

AIR POLLUTION CONTROL EQUIPMENT

Debonding of brake shoes and reclamation of electrical windings conducted in a single-chamber unit can be easily controlled by using an afterburner as described in the first part of Chapter 5.

Two basic configurations of equipment using afterburners effectively accomplish these reclamation processes with a minimum discharge of air contaminants. One is a single structure housing the primary and secondary combustion chambers, while the other consists of two separate pieces of equipment, a primary chamber and an afterburner or secondary chamber. Variations in the design of these two configurations are many, and the final selection of a particular design is based upon considerations such as space limitation, process conditions, maintenance, capital investment, and operating expenses. In designing an effective afterburner, the size and appurtenances of the primary ignition chamber must be known or be initially designed.

Primary Ignition Chamber

The size of the primary chamber is determined from the production rate or volume of the batch charge desired. On the average, 1 cubic foot of space holds in random arrangement 27 brake shoes, or 34 automotive field coils, or 10 automotive armatures. In sizing the primary chamber, additional space is provided over that space occupied by the charge, to make it easier to load and unload. For example, in a batch process, 350 automotive generator field coils or 200 average-size brake shoes can be randomly placed in a 55-gallon drum.

Table 134. STACK EMISSIONS FROM RECLAIMING ELECTRICAL WINDINGS IN SINGLE CHAMBERS WITHOUT CONTROLS

Item	Test No.				
	C-342	C-497	C-542	C-541-1	C-541-3
Composition of charge	100-hp generator stator	14 pole pieces	200 auto armatures	Auto armatures	Auto field coils
Charge weight, lb	--	3,825	161	1,034	356
Duration of test, min	22.5[a]	60	55	45.4	16
Combustible content of charge, wt %	5	5	1.7	1.2	5.9
Stack gas flow rate, scfm	320	400	210	790	950
Average gas temperature, °F	680	350	360	470	290
Particulate matter, gr/scf at 12% CO_2	1.9	1.1	3.3	0.54	1.33
Particulate matter, lb/hr	2.43	0.65	1.64	1.04	2.51
Sulfur dioxide, lb/hr	0.13	--	0	0.02	0.13
Carbon monoxide, lb/hr	1.90	0.35	0.50	1.39	4.72
Organic acids as acetic acid, lb/hr	0.35	0.33	0.62	0.42	1.01
Aldehydes as formaldehyde, lb/hr	0.08	0.079	0.29	0.13	0.49
Nitrogen oxides as NO_2, lb/hr	3.07	--	0.03	0.12	0.08
Hydrocarbons as hexane, lb/hr	Nil	--	0.16	0.09	0.11
Smoke emissions, opacity range Ringelmann chart	15 to 30%	--	0 to 100%	0 to 30% white	0 to 80% gray
Odors					

[a]Test duration does not include preheat period.

Primary burner capacity is computed by conventional heat and material balances to determine the amount of heat necessary to raise the temperature of the material being processed to 850°F. This temperature ensures ignition of combustibles, and maintenance of the temperature necessary for complete combustion. Gas burners must supply sufficient heat not only for ignition, but also to sustain burning. The lower the combustible content of the charge, the more heat that must be supplied by the primary burners. Consequently, primary burners are sized for minimum combustible content of the charge.

Adjustable air ports near the bottom of the primary chamber should be large enough to provide theoretical air plus 100 percent excess air. These ports should be sized to provide this quantity of air for the maximum combustible content of the charge.

Secondary Combustion Chamber

The mixing chamber or afterburner is designed for maximum effluent from the primary chamber using conventional heat and material balances. For a given charge, maximum effluent occurs when the combustible content of the charge is at a maximum. The mixing chamber burner or afterburner must be capable of raising the temperature of the maximum quantity of effluent expected from a temperature of 850° to 1,400°F. These burners are positioned to blanket the cross-sectional area of the afterburner completely with flame.

The cross-sectional area of the mixing chamber is based upon an average gas velocity ranging from 20 to 30 fps for the total effluent. Gas velocities in this range promote turbulent mixing of the gaseous effluent from the ignition chamber with the flames from the mixing chamber burner. Baffles and abrupt changes in direction of gas flow also promote turbulent mixing, which is essential for complete combustion. The mixing chamber or afterburner should be of sufficient length to allow a residence time of at least 0.15 to 0.2 second.

Secondary air ports should provide theoretical air for maximum combustible content of the charge.

Stack

In designing a stack for minimum height, stack gas velocities should not exceed 20 fps at maximum temperatures to minimize the effects of friction. Effective draft is computed as theoretical stack draft minus friction losses at design flow conditions. An effective draft or negative static pressure of from 0.05 to 0.10 inch WC should be available in the ignition chamber when the unit is operating at rated capacity.

Emissions

Stack emissions from brake-debonding and reclamation equipment using secondary combustion are listed in Table 135. Note that, in all cases, the carbon monoxide has been eliminated, and the particulate matter reduced by approximately 90 percent when compared with emissions from uncontrolled units cited in Table 134.

Typical Reclamation Equipment

The multiple-chamber incinerator previously discussed in the first two parts of this chapter can be adapted for these processes. Figure 340 shows an incinerator of this kind that differs from a standard multiple-chamber incinerator by its oversize ignition chamber and the absence of the grates and ash pits. The third chamber (the combustion chamber) is less useful because there is little or no fly ash to be removed from the gas stream. The combustion chamber does, however, complete the secondary combustion process and protect the stack lining from direct flame impingements.

Primary burners are of the atmospheric type and can be mounted through the sides and at the bottom of the primary chamber. An alternative arrangement consists of dual-pipe burners placed across the base of the primary chamber, which results in more even distribution of heat over the cross section of this chamber. These burners must, of course, be positioned so that there will be no interference when the racks containing the charge of material are inserted or removed. Mixing chamber burners are located in the same position as shown for a standard multiple-chamber incinerator. Air ports are also similar in construction and location to those mounted on a standard multiple-chamber incinerator.

Another satisfactory single-structure design consists of only two refractory-lined chambers, as illustrated in Figure 341. It differs from the conventional three-chamber unit already described only in that the third chamber has been eliminated.

A relatively simple design using a separate primary chamber and afterburner is shown in Figure 342. The primary chamber consists of a tubular frame with sheet metal siding. Drilled-pipe gas burners are installed in the bottom of the chamber. The material to be reclaimed is placed in a 55-gallon drum with a perforated bottom, and the drum is placed in the primary chamber. The contents of the drum are heated and ignited by the pipe burners, and the hot gases and smoke flow to an afterburner mounted on top of the primary chamber. Heat is supplied to the afterburner by a fan-air burner firing tangentially into the refractory-lined chamber. This equipment is usually equipped with

Table 135. STACK EMISSIONS FROM DEBONDERS AND RECLAMATION EQUIPMENT USING SECONDARY COMBUSTION

Item	Test No.		
	C-286	C-541-4	C-497
Equipment description	Dual-chamber brake debonder	M-C incinerator	Oven with afterburner
Composition of charge	480 brake shoes	Auto field coils	(14 generator pole pieces)
Charge weight, lb	--	386	3,825
Combustible content, wt %	--	6.7	
Duration of test, min	30	8	60
Stack gas flow rate, scfm	181	990	950
Stack gas temperature, °F	999	1,340	1,250
Secondary afterburner temperature, °F			2,000
Particulate matter, gr/scf at 12% CO_2	0.24	0.04	0.016
Particulate matter, lb/hr	0.12	0.37	0.059
Sulfur dioxide, lb/hr	0.12	0	--
Carbon monoxide, lb/hr	0	0	0
Organic acids as acetic acid, lb/hr	0.08	0.90	--
Aldehydes as formaldehyde, lb/hr	--	0.08	0.079
Nitrogen oxides as NO_2, lb/hr	--	0.30	
Hydrocarbons as hexane, lb/hr	--	0.23	
Smoke emissions, opacity range Ringelmann chart	0	0	0

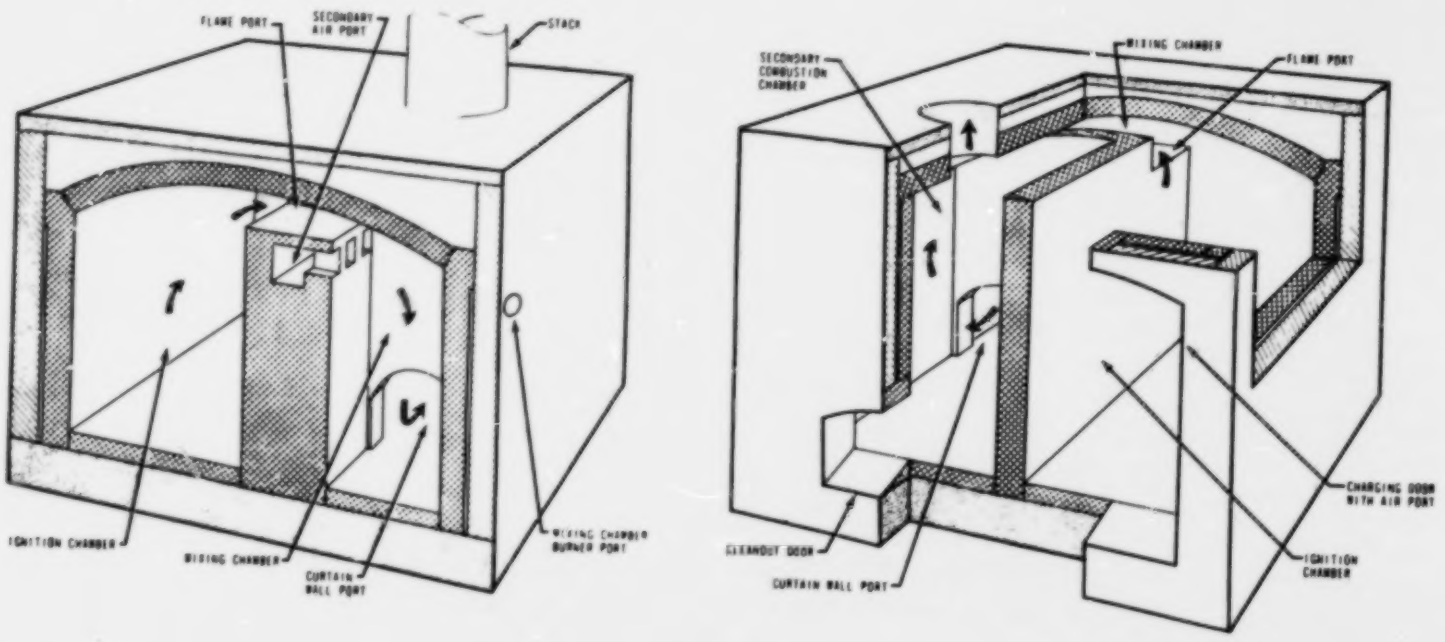


Figure 340. Multiple-chamber incinerator adapted for use in reclamation processes (see Figure 308).

a stack that is 16 to 20 feet above ground level. Since good heat control is difficult to maintain, this equipment is more suitable for brakeshoe debonding than for electrical-winding and armature core reclamation.

In some cases, an oven vented to an afterburner is used. This oven differs from the refractory-lined primary chamber in that there is no direct flame contact with the charge, and the hot combustion gases are recirculated within the chambers for

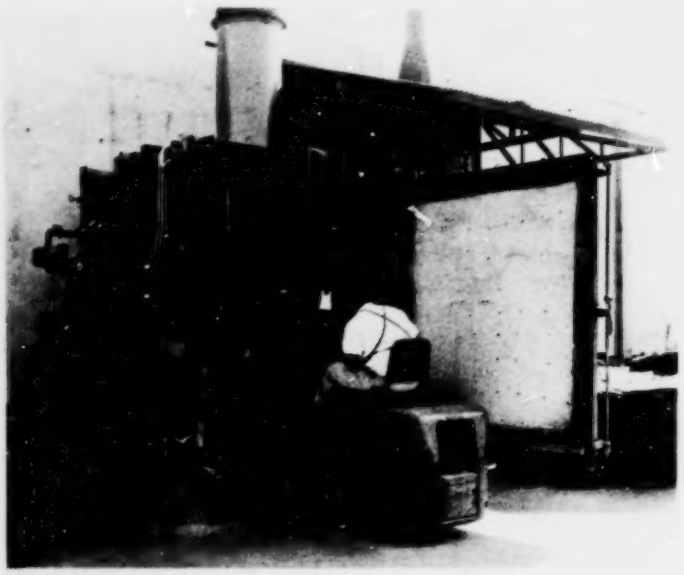


Figure 341. Dual-chamber reclamation furnace (Auto Parts Exchange, City of Industry, Calif.).

more precise heat conservation and control. The installation of a cam-operated temperature controller makes possible a gradual elevation of primary-chamber temperature and an exact control of temperature over extended periods of time. This type of control is widely used for processing electrical windings from motors and generators where warpage of the laminations is to be avoided. This type of reclamation equipment lends itself to either the batch or continuous process.

A continuous-process device is shown in Figure 343; it consists of an endless-chain conveyor that transports material into a tunnel-like chamber. The products of combustion, smoke, and volatile components are collected near the center of the tunnel and vented to an afterburner. Asbestos curtains are installed where the parts enter and leave the chamber; they conserve heat by reducing the induction of air. Continuous-process equipment of this type usually has a higher heat requirement than corresponding batch equipment does because of the induction of excessive air at the openings to the primary chamber.

Another unique design, which can be used for semicontinuous operation, consists of two refractory-lined compartments connected back to back. While material is being processed in one of the compartments, the other compartment is being unloaded and reloaded. Again, the smoke and gaseous effluents are vented to a vertical afterburner and stack.

Standards for Construction

Materials and methods of construction are similar to those used for multiple-chamber incinerators, as described in the second part of this chapter. Exterior shells are constructed of 12-gage-minimum-thickness steel plates properly placed and supported by external structure members. Block insulation with a minimum thickness of 2 inches and a service temperature of 1,000°F is normally used between the steel shell and the refractory lining to conserve heat and protect the operator. High-heat-duty firebrick with adequate expansion joints is used for lining the primary chamber as well as the secondary chamber or afterburner. Stacks are constructed of 10-gage steel plates and are lined with 2 inches of insulating firebrick or castable refractory having a minimum service temperature of 2,000°F.

Illustrative Problem

Problem:

Design batch equipment to debond 200 average-size brake shoes or 175 average-size automobile generator field coils--each batch will require a 30-minute period.

Solution:

1. Ignition chamber dimensions:

   200 average-size brake shoes weigh 350 lb

   175 average-size field coils weigh 350 lb

   Average bulk density of brake shoes is 27 units/ft^3

   Average bulk density of field coils is 34 units/ft^3

   Brake shoes with 25% free volume

   $$(200 \text{ shoes})\left(\frac{1 \text{ ft}^3}{27 \text{ shoes}}\right)\left(\frac{1}{0.75}\right) = 10 \text{ ft}^3$$

   Field coils with 50% free volume

   $$(175 \text{ coils})\left(\frac{1 \text{ ft}^3}{34 \text{ coils}}\right)\left(\frac{1}{0.5}\right) = 10 \text{ ft}^3$$

   Primary-chamber dimensions

   2 ft wide x 3 ft high x 1 ft 8 in. deep

2. Design capacity of primary gas burner:

   Design for minimum combustibles content of 3% by weight.

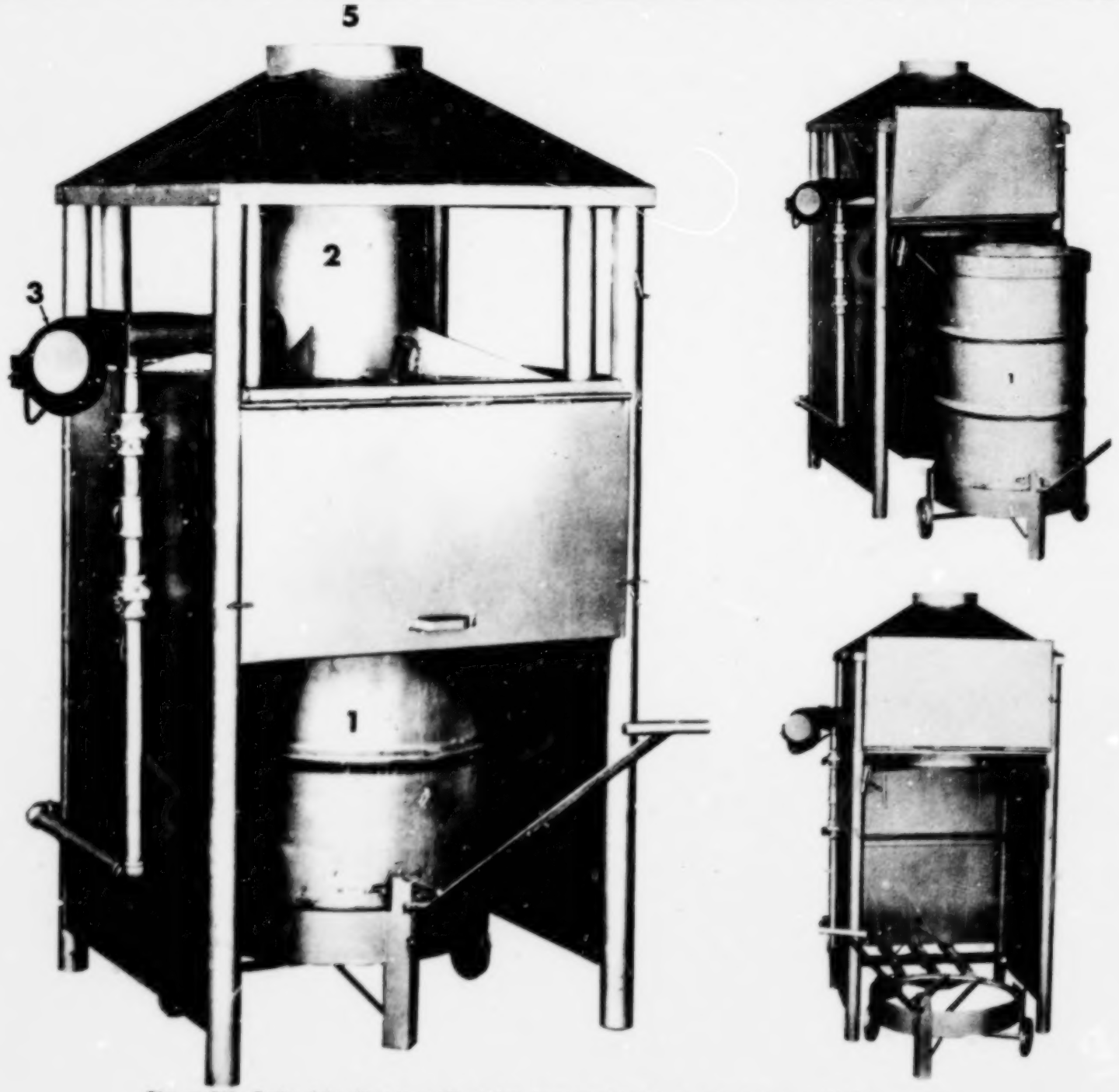


Figure 342. Brake debonding in a 55-gallon drum venting to an afterburner: (1) Drum holding brakeshoes, (2) secondary combustion chamber, (3) secondary burner (afterburner), (4) primary burner--pipe type, (5) stack (Griggs Specialty Products, Huntington Park, Calif.).

(a) Heat required to raise temperature of charge from 60° to 900°F. Neglect moisture in charge:

Average specific heat of brakeshoes or automobile generators is 0.21 Btu/lb-°F

$$Q = (W)(Cp)(T_2 - T_1)$$

where

Q = heat required, Btu/hr

W = weight of charge, lb/hr

Cp = average specific heat of charge, Btu/lb-°F

T_2 = final temperature, °F

T_1 = initial temperature, °F

$$Q = (0.97)\left(\frac{2 \text{ charges}}{\text{hr}}\right)\left(\frac{350 \text{ lb}}{\text{charge}}\right)$$
$$(0.21 \text{ Btu/lb-°F})(900°F - 60°F)$$

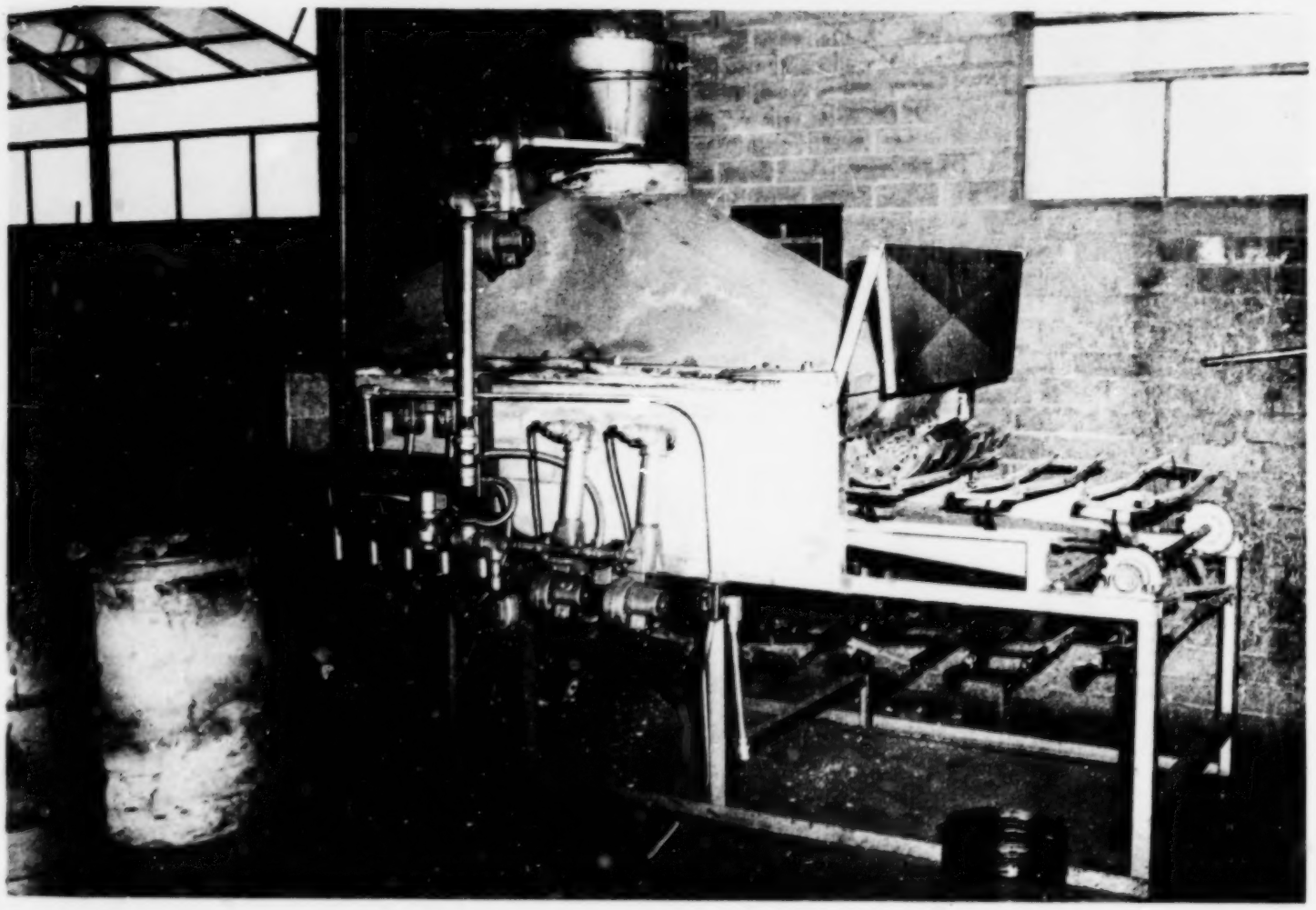


Figure 343. Continuous brakeshoe debonder (Wagner Electric Corp., El Segundo, Calif.).

Q = 119,800 Btu/hr

(b) Heat required to raise products of combustion from 60° to 900°F:

Assume combustibles have a composition equivalent to PS-400 fuel oil. Design for 200% excess air, 40% saturated. From Table D6, Appendix D, products of combustion weigh 41.47 lb from combustion of 1 lb combustible (PS-400 fuel). Average specific heat of products of combustion is 0.26 Btu/lb-°F.

Weight of products of combustion, W:

$$W = (0.03)\left(\frac{350\ \text{lb}}{\text{charge}}\right)\left(\frac{2\ \text{charges}}{\text{hr}}\right)\left(\frac{41.47\ \text{lb}}{\text{lb}}\right)$$

= 870 lb/hr

Heat required

$$Q = (W)(Cp)(T_2 - T_1)$$

where

Q = heat required, Btu/hr

W = weight of products of combustion, lb/hr

Cp = average specific heat of products of combustion, Btu/lb-°F

T_2 = final temperature, °F

T_1 = initial temperature, °F

Q = (870 lb/hr)(0.26 Btu/lb-°F)(900°F - 60°F)

= 190,000 Btu/hr

(c) Net heat required for process:

(a) + (b) = Total net heat

119,800 Btu/hr + 190,000 Btu/hr = 309,800 Btu/hr

(d) Gross heat required for process:

Assume radiation, convection, and storage heat losses are 30% of gross heat input. Net heat available for process is 70% of gross heat input.

$$\frac{309,800 \text{ Btu/hr}}{0.70} = 442,000 \text{ Btu/hr}$$

(e) Heat supplied by combustibles in charge:

From Table D5, Appendix D, the gross heat of combustion from 1 lb combustible (PS-400 fuel oil) is 18,000 Btu/lb

$$(0.03)\left(\frac{350 \text{ lb}}{\text{charge}}\right)\left(\frac{2 \text{ charges}}{\text{hr}}\right)(18,000 \text{ Btu/lb})$$

= 378,000 Btu/hr

(f) Net heat required in primary chamber:

442,000 Btu/hr - 378,000 Btu/hr = 64,000 Btu/hr

(g) Primary burner capacity:

From Table D7, Appendix D, the calorific value of natural gas is 765.3 Btu/scf at 900°F.

$$\frac{64,000 \text{ Btu/hr}}{765.3 \text{ Btu/ft}^3} = 84 \text{ cfh}$$

3. Size of combustion air ports:

Design all port areas 100% oversize.

Assume 100% excess air through the primary air port and theoretical air through the secondary port.

Design for a maximum combustible content of the charge of 5% by weight. Assume the draft at all ports is 0.10 in. WC. From Table D8, Appendix D, 0.10 in. WC is 1,255 fpm

From Table D6, Appendix D, 363 scf of combustion air is required for combustion of 1 lb (PS-400 fuel oil) at 100% excess air, and 177 scf of combustion air is required for combustion of 1 lb (PS-400 fuel oil) at theoretical air.

(a) Primary air port:

Maximum airflow.

$$(0.05)\left(\frac{350 \text{ lb}}{\text{charge}}\right)\left(\frac{2 \text{ charges}}{\text{hr}}\right)\left(\frac{363 \text{ ft}^3}{\text{lb}}\right) = 12,700 \text{ cfh}$$

or 212 cfm

$$\text{Port size} = \left(\frac{212 \text{ cfm}}{1,255 \text{ fpm}}\right)(2) = 0.338 \text{ ft}^2$$

or 48.6 in.^{2}

(b) Secondary air port:

Maximum airflow.

$$(0.05)\left(\frac{350 \text{ lb}}{\text{charge}}\right)\left(\frac{2 \text{ charges}}{\text{hr}}\right)\left(\frac{177 \text{ ft}^3}{\text{lb}}\right) = 6,200 \text{ cfh}$$

or 103 cfm

$$\text{Port size} = \left(\frac{103 \text{ cfm}}{1,255 \text{ fpm}}\right)(2) = 0.1640 \text{ ft}^2$$

23.5 in.^{2}

4. Design capacity of secondary burner (afterburner):

Design for a maximum combustible content of charge of 5% by weight.

(a) Maximum products of combustion with no secondary air:

Weight of products of combustion of natural gas with 20% excess air is 0.999 lb/scf.

$$(0.05)\left(\frac{350 \text{ lb}}{\text{charge}}\right)\left(\frac{2 \text{ charges}}{\text{hr}}\right)\left(\frac{41.47 \text{ lb}}{\text{lb}}\right) = 1,460 \text{ lb/hr}$$

$$(84 \text{ cfh natural gas})(0.999 \text{ lb/scf}) = \frac{84 \text{ lb/hr}}{1,544 \text{ lb/hr}}$$

(b) Heat required to raise products of combustion from 900° to 1,400°F:

$$Q = W C_p (T_2 - T_1) \text{ see item 2(b).}$$

$$Q = (1,544 \text{ lb/hr})(0.26 \text{ Btu/lb-°F})(1,400°F - 900°F)$$

$$Q = 201,000 \text{ Btu/hr}$$

(c) Burner capacity:

From Table D7, Appendix D, the calorific value of natural gas at 1,400 °F is 616 Btu/scf.

$$\frac{201,000 \text{ Btu/hr}}{616 \text{ Btu/scf}} = 326 \text{ cfh}$$

5. Size of mixing chamber (afterburner):

From Tables D6 and D7, Appendix D, there are 540 scf of products from combustion of 1 lb combustible (PS-400 fuel oil) at 200% excess air, and 13.53 scf of products of combustion from 1 scf natural gas at 20% excess air.

(a) Cross-sectional area of inlet duct:

Design for gas flow of 20 fps at 900°F

Gas flow at 60°F

Combustibles at 200% excess air

$$(0.05)\left(\frac{350 \text{ lb}}{\text{charge}}\right)\left(\frac{2 \text{ charges}}{\text{hr}}\right)\left(\frac{540 \text{ ft}^3}{\text{lb}}\right) = 18,900 \text{ cfh}$$

Natural gas at 20% excess air

$(84 \text{ cfh})(13.53 \text{ ft}^3/\text{ft}^3) = 1,133 \text{ cfh}$

20,023 cfh

or 333 cfm

or 5.55 cfs

Cross-sectional area

$$(5.55 \text{ scf})\left(\frac{1,360°\text{R}}{520°\text{R}}\right)\left(\frac{1}{20 \text{ fps}}\right) = 0.728 \text{ ft}^2$$

(b) Cross-sectional area of mixing chamber (afterburner):

Design for gas flow of 25 fps at 1,400°F

Gas flow at 60°F

Combustibles from primary chamber 20,055 cfh

Secondary gas burner

$(326 \text{ cfh})(13.53 \text{ ft}^3/\text{ft}^3)$ 4,410 cfh

24,465 cfh

or 408 cfm

or 6.8 cfs

Cross-sectional area

$$(6.8 \text{ cfs})\left(\frac{1,860°\text{R}}{520°\text{R}}\right)\left(\frac{1}{25 \text{ fps}}\right) = 0.975 \text{ ft}^2$$

(c) Length of mixing chamber (afte· burner):

Design for residence time of 0.15 second

Length = (25 fps x 0.15 second) = 3.75 ft

6. Stack diameter:

Design for a gas velocity of 20 fps at 1,200°F

Cross-sectional area

$$\text{Area} = (1.8 \text{ cfs})\left(\frac{1,660°\text{R}}{520°\text{R}}\right)\left(\frac{1}{20 \text{ fps}}\right) = 1.08 \text{ ft}^2$$

Stack diameter 13.9 in.

Select 14-inch diameter.

7. Stack height:

(a) Theoretical draft for a 10-ft section at 1,200°F:

$$D_t = 0.52 \text{ PH} \left(\frac{1}{T_1} - \frac{1}{T}\right)^*$$

where

D_t = theoretical draft, in. WC

P = atmospheric pressure, lb/in.^{2} absolute

H = stack height, ft

T = temperature of stack gases, °R

T_1 = temperature of air, °R

$$D_t = (0.52)(14.7)(10)\left(\frac{1}{520} - \frac{1}{1,660}\right)$$

$$D_t = (76.5) \quad (0.00192 - 0.00060)$$

D_t = 0.101 in. WC

(b) Stack friction for a 10-ft section at 1,200°F:

$$F = \frac{(0.008)(H)(V)^2}{(D)(T)}\ ^\dagger$$

where

F = friction, in. WC

H = stack height, ft

*Kent, 1930.

†Griswold, 1946.

V = velocity, fps

D = stack diameter, ft

T = absolute stack temperature, °R

$$F = \frac{(0.008)(10)(20)^2}{(1.25)(1,660)} = 0.015 \text{ in. WC}$$

(c) Net effective draft for a 10-ft section:

(a) - (b) = Net draft

0.101 in. WC - 0.015 in. WC = 0.086 in. WC

(d) Ignition chamber:

Assume static pressure of 0.05 in. WC

(e) Friction loss in secondary-combustion zone:

(1) Contraction loss into secondary zone:

Assume 0.5 VP loss at 20 fps and 900°F

Gas velocity 20 fps at 900°F

$$V = 2.9\sqrt{(T)(h)}\ ^*$$

where

V = gas velocity, fps

T = absolute temperature, °R

h = static pressure, in. WC

$$h = \left(\frac{V}{2.9}\right)^2\left(\frac{1}{T}\right)$$

$$h = \left(\frac{20}{2.9}\right)^2\left(\frac{1}{1,360}\right)$$

h = 0.035 in. WC

$$\text{Contraction loss}\left(\frac{0.035 \text{ in. WC}}{\text{VP}}\right)(0.5 \text{ VP})$$

= 0.017 in. WC

(2) Design for two 90-degree bends in secondary zone:

Assume 1-VP loss for each 90-degree bend and that the products of combustion have a composition equivalent to that of air.

Gas velocity 25 fps and 1,400°F

$$h = \left(\frac{V}{2.9}\right)^2\left(\frac{1}{T}\right)$$

$$h = \left(\frac{25}{2.9}\right)^2\left(\frac{1}{1,860}\right)$$

h = 0.04 in. WC

$$\text{Loss}\left(\frac{0.04 \text{ in. WC}}{\text{VP}}\right)(2 \text{ VP}) = 0.08 \text{ in. WC}$$

(3) Friction loss through secondary zone:

$$F = \frac{0.008\,(H)(V)^2}{DT}$$ see item 7(b)

$$F = \frac{(0.008)(3.75)(25)^2}{(1.25)(1,860)}$$

F = 0.008 in. WC

(f) Total effective draft required from stack:

(d) + (e)(1) + (e)(2) + (e)(3) = total

0.050 in. WC + 0.017 in. WC +
0.080 in. WC + 0.008 in. WC
= 0.155 in. WC

(g) Stack height:

Let H = stack height, ft

$$\left(\frac{0.086 \text{ in. WC}}{10\text{-ft stack}}\right)(H) = 0.155 \text{ in. WC}$$

H = 18.0 ft

DRUM RECLAMATION FURNACES

INTRODUCTION

Drum reclamation constitutes an important segment of the salvage industry. In this operation, steel drums used in transporting and storing chemicals and other industrial materials are cleaned, repaired, and repainted for reuse. Although steel drums are made in many sizes, 30-gallon and 55-gallon sizes are the two most common.

*Research-Cottrell, Inc.

Drum construction, closed-top or open-top, determines the process selected for the cleaning phase of reclamation. Closed-top drums are cleaned with solvents, hot caustic, or other chemical solutions; open-top drums can be cleaned not only with chemicals but by burning the combustible materials adhering to the drum surfaces. Since cleaning open-top drums by incineration can usually be done at a cost lower than that of chemical cleaning, it has been widely adopted by industry. This incineration process and its related equipment are discussed here.

Description of the Furnace Charge

Typical materials to be burned from open-top steel drums include asphalt compounds, sealants, paints, lacquers, resins, plastics, lard, foodstuffs, grease, solvents, and numerous other industrial liquid and solid materials. Of course, the variable amount of residue remaining in the drums results not only from the nature of the contained material but also from the unpredictable degree of thoroughness with which the drum is emptied. Although a few 55-gallon drums received for processing may contain as much as 20 pounds of combustible material, over 90 percent normally contain less than 3 or 4 pounds; most of the 30-gallon drums contain correspondingly less. In current plant operations in Los Angeles County, 55-gallon drums constitute 75 to 80 percent of total open-top drums reclaimed by incineration, with 30-gallon drums making up the balance.

Description of the Process

Open-top steel drums may be cleaned by burning out the residual materials in the open or in refractory-lined chambers. The drums are generally in an inverted position, with the open top down so that residual materials have a chance to melt and flow free of the drum as well as burn. In the furnace, flame applied to the exterior surface to burn off grease, paint, and other coatings is also carried into the interior of the drum by ignition of molten material dripping from the interior surfaces.

After the combustibles are consumed, the drums are allowed to cool. They are then shot peened to remove all ash and char. Dents or surface irregularities are removed by special rolling machines; finally, the drums are tested hydraulically and protective coatings applied.

As expected, burning residue from drums in refractory-lined furnaces is more efficient than burning in the open since heat is conserved within the furnace, and combustion air can be controlled.

Refractory-lined furnaces can be classified as to type of process--batch or continuous. A batch-type single-chamber furnace, as shown in Figure 344, is designed to accommodate one drum at a time; its capacity is usually limited to less than 30 drums per hour. Continuous-type furnaces, depicted in Figure 345, are constructed in the form of a tunnel and are usually designed to burn about 150 drums per hour.

Drums are supported upside down upon a drag conveyor, the drum covers sometimes resting across adjacent drum bottoms. They move through the tunnel where burner flames impinge on the exterior surfaces. Exterior coatings burn and peel off while residual materials inside catch fire, melt, and drip onto a flat surface at the base of the conveyor. Although melted materials may burn upon the flat surface, they are scraped along and carried from the furnace by the returning flights of the conveyor. Water sprays are used to quench any burning materials before they leave the furnace.

Drums are spaced at least 3 or 4 inches apart on the drag conveyor to allow flames from the primary burners to cover the drum surface completely.

THE AIR POLLUTION PROBLEM

The practice of burning off organic residues, paint, and other materials from drums either in the open or in a single refractory-lined chamber results in the emission of large quantities of smoke, odor, and combustion contaminants. These emissions can occur not only from the fan discharge or stack but also from the furnace ports and other openings.

AIR POLLUTION CONTROL EQUIPMENT

There is no feasible way of controlling emissions from open burning. However, emissions can be controlled from properly designed single-chamber furnaces by venting to an afterburner or a secondary combustion chamber similar in arrangement to the mixing chamber of a multiple-chamber incinerator as described in the first two parts of this chapter. Information on the design of afterburners is given in the first part of Chapter 5. In designing an effective afterburner or an equally effective secondary combustion chamber, however, the size and appurtenances of the primary chamber must be selected first.

Primary Ignition Chamber, Batch Type

A batch-type chamber, shown in Figure 344, is designed to hold one 55-gallon drum with a space of 6 inches or more between the drum and refractory walls. Obviously, this same chamber can also be used to process the smaller 30-gallon drum. Since the drum is burned upside down to allow re-

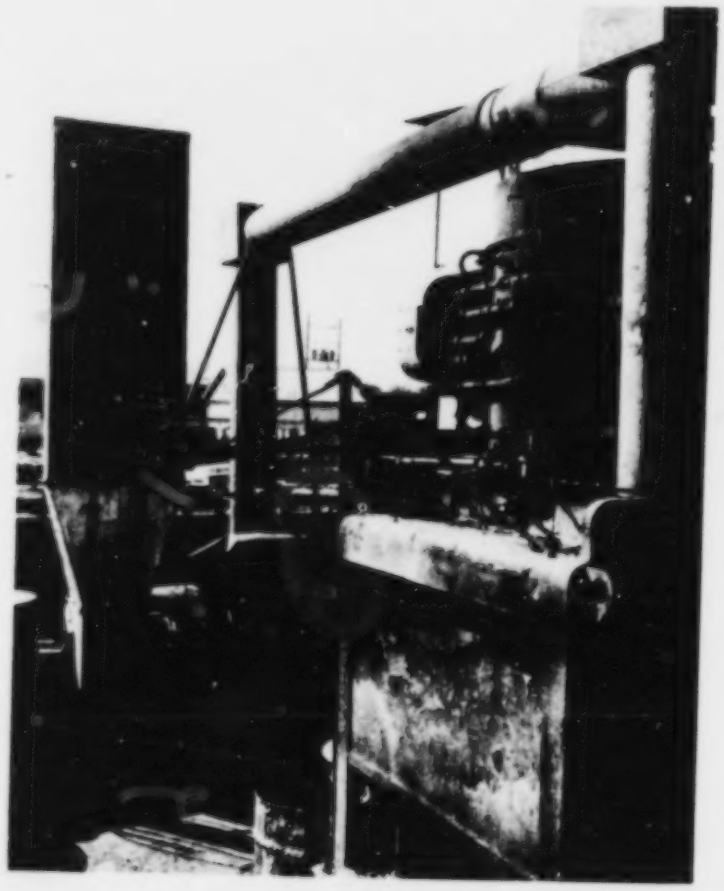


Figure 344. Batch-type drum reclamation furnace with an afterburner (Apex Drum Co., Los Angeles, Calif.).

sidual materials to melt and flow from the drum, removing the products of combustion from the bottom of the chamber rather than the top is advantageous in order to promote the carryover of flames into the drum interior.

Several gas burners are strategically arranged around the chamber so as to cover the exterior drum surface completely with flame. These gas burners usually operate at 20 percent excess combustion air. Air is supplied for combustion of drum residue through air ports in the sides of the chamber.

For design purposes, air ports should permit the induction of 200 percent excess air for combustion of 4 pounds of combustible materials within a nominal 4-minute period. The composition of the combustible is considered equivalent to US Grade 6 fuel oil. The primary burners should be capable of raising the temperature of the induced air to 1,000°F and of the steel drum to at least 900°F, based upon the most severe operating condition--that of maximum air induction and negligible combustible materials on the drum. Yet, excessive drum temperatures must be avoided to prevent drum warpage and scale formation.

Primary Ignition Chamber, Continuous Type

Although the design of a continuous-type ignition chamber for reclaiming 55- and 30-gallon drums involves the same basic factors of combustion as those for the batch-type chamber, certain factors such as combustion volume, burner capacity, and combustion air differ markedly for this dynamic process.

The process requires sustained temperatures for removal by melting, and virtually complete combustion of all residue and surface coatings on the drum during its period of conveyance through the furnace. As shown in Figure 346, the furnace is constructed in the form of a tunnel that can be conveniently divided into three zones. After entering the tunnel, the drums pass through the preheat zone where they are heated by radiation from the ignition zone; they then pass through the ignition zone where combustibles in direct contact with burner flames ignite and burn; lastly, they pass through the cooling zone where a small amount of burning continues until combustion is complete and the drums are cooled by induced air.

Of necessity, various dimensions of the tunnel are established by the size of a standard 55-gallon drum, which averages 24 inches in diameter and 35 inches in height. With only minor adjustments, this tunnel can also serve in processing the smaller 30-gallon drum, which averages 19 inches in diameter and 29 inches in height.

Although combustible content of the combustible materials on each drum can vary drastically, over 90 percent of all drums as received for processing contain from nearly zero to about 4 pounds of combustible materials. Fortunately, it is possible to design a continuous furnace that will process drums containing this range of combustible without requiring extensive and continual adjustments.

Combustion dynamics do, however, require a furnace of an optimum size to accommodate the variations in burning rates among the drums as they move along the tunnel so that all products of combustion are retained for admission to the afterburner or secondary combustion chamber. To process an average drum containing anywhere from zero to 4 pounds of combustibles requires an average of 4 minutes. The 55-gallon drums must be spaced on the conveyor not less than 3 or 4 inches apart to allow complete flame coverage of the exterior surface by flame passage among the drums. In processing 150 drums per hour or 2.5 drums per minute, with a design space of 5 inches between drums, the conveyor must move at the rate of 6 fpm; therefore, the combined length of the ignition zone and the cooling zone in which all burning takes place is 24 feet. Most drums are allowed to reach about 900°F in the furnace whereupon they begin to glow

Figure 345. Continuous-type drum reclamation furnace with an afterburner (D and M Drum Company, South El Monte, Calif.).

a dull red, but the temperature of the drum must not exceed a bright orange color of 1,000°F; otherwise excessive drum warpage and scaling occurs with a subsequent loss in the strength of the steel. Of course, drum temperatures do not represent the temperature of the exhaust gases leaving the ignition zone.

Optimum furnace performance requires that the furnace be adjustable in conveyor speed and burner setting. If drums containing negligible combustibles are processed exclusively, the speed of the conveyor and production rate can be increased. Conversely, if so-called difficult drums, drums containing more than 4 pounds of highly combustible asphaltic and adhesive compounds, are burned exclusively, they must be spaced 6 feet or more apart on the conveyor moving at a normal speed of 6 fpm in order to retain the same residence time but prevent overloading the afterburner.

Air for combustion of combustible materials on the drums is supplied through minimum size drum inlet and outlet openings on the ends of the tunnel, in order to maximize indraft velocities.

A practical clearance of about 1 to 2 inches is provided between the 55-gallon drum and the walls and arch of the refractory-lined opening. The area required for the protruding conveyor through which air can be induced should also be kept as small as possible. The internal dimensions of the opening are 26 inches wide by 36-1/2 inches high. A space for the conveyor of about 14 square inches is provided at each end. The openings should extend at least 30 inches, which exceeds the minimum 27- or 29-inch space allowance for 55-gallon drums upon the conveyor. At least one drum should always be in position to blank off most of the area of the opening and thereby create high indraft velocities.

Air curtains may also be installed at the ends of the tunnel to help prevent the escape of smoke caused by air currents or wind across the face of the tunnel. They consist of drilled pipe located around the inside edge of the tunnel opening through which air is injected across the face of the opening to flow inward to the center of the tunnel.

An average indraft velocity of 200 fpm through the tunnel openings without drums on the conveyor sup-

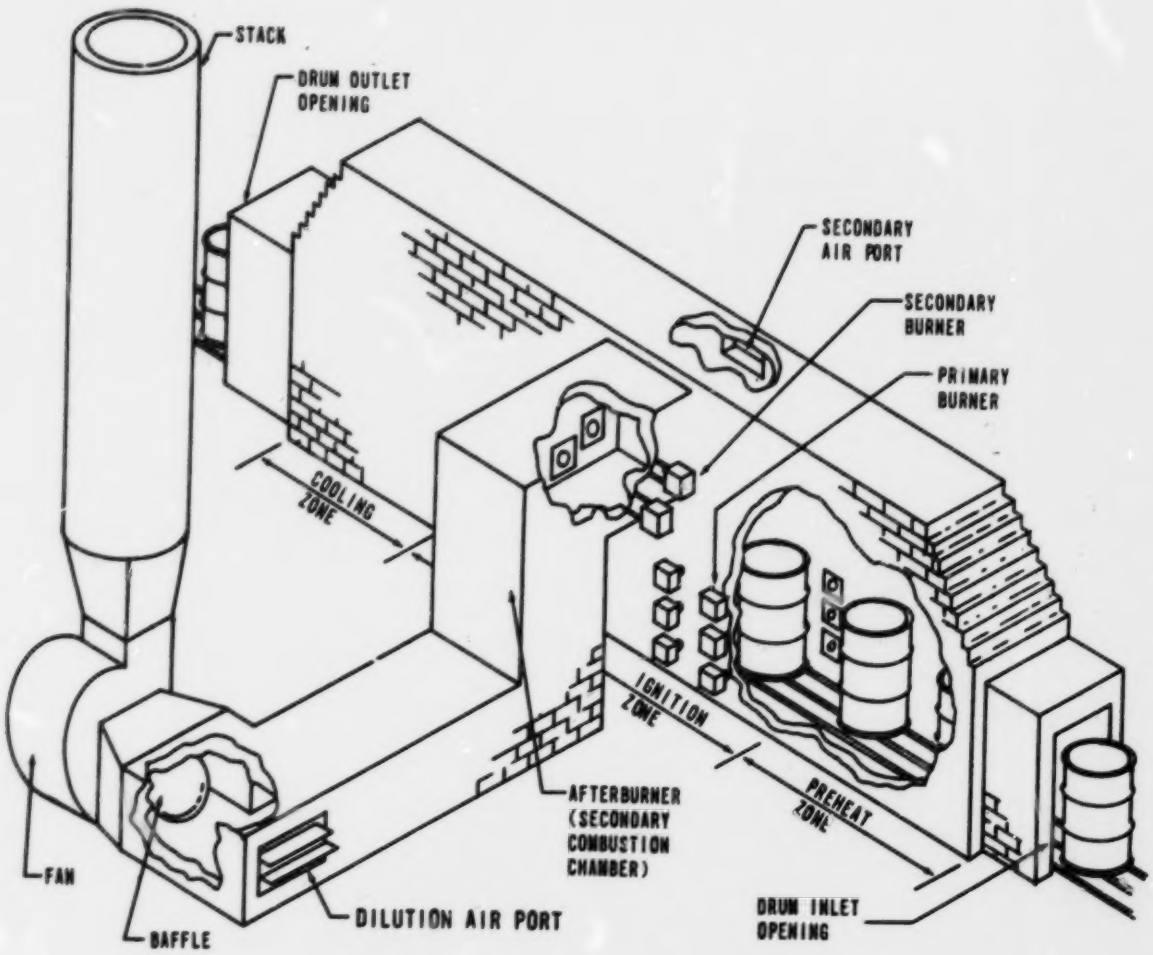


Figure 346. Diagram of a continuous-type drum reclamation furnace with an afterburner.

plies approximately 50 percent in excess of theoretical air for burning a maximum of 4 pounds of combustible per drum. In this case, the combustibles are considered equivalent in composition to US Grade 6 fuel oil. Nevertheless, in addition to combustion air through the tunnel openings, up to 100 percent of theoretical air should be supplied through a secondary air port for operating flexibility.

As shown in Figure 346, the ignition zone is located at the central part of the tunnel. Primary burners are designed to attain drum temperatures of 900°F and average effluent temperatures of about 1,000°F, based upon the drums' containing no appreciable combustible residue. The volume of the ignition zone may be determined from a heat release factor of about 22,000 Btu per hour per cubic foot with primary burners at maximum design capacity and drums containing negligible combustible materials. This factor is in line with the heat release factors for oil-fired furnace fireboxes operating at temperatures of less than 1,800°F.

Since flames must effectively cover the exterior surface of the drum, the burners are mounted in refractory walls 6 inches from the sides of the 55-gallon drum. Thus, internal width of the zone is 36 inches. The arch rises about 78 inches, an arbitrary design figure, above the base of the conveyor to provide volume for collecting the products of combustion.

As shown in Figure 346, only the ignition zone contains primary burners. These burners are arranged in eight vertical rows of two or three burners with four rows on each side of the chamber spaced about 2 to 2-1/2 feet apart.

The rows are offset 1 to 1-1/4 feet from opposite sides of the chamber to prevent the flames from the burner on one side of the chamber from directly opposing flames from burners on the opposite side.

Burners are mounted on at least two levels to cover the surface of the drum completely with flame. If

each row contains three burners, the burners are mounted 12 inches apart vertically, and the bottom burner is mounted 6 inches above the top of the conveyor. The first row of burners on each side is usually set for operation at maximum capacity, its flame travel extending about three-fourths of the width of the zone. The burners in the rows that follow are adjusted manually, usually at reduced capacity, or controlled automatically by a signal from a thermocouple at the inlet to the afterburner.

The cooling zone provides for completion of the combustion process within the nominal 4-minute design residence time. Usually only a small percentage of the total combustion occurs within the zone.

After the length of the ignition zone is computed, the length of the cooling zone is determined in feet by subtracting from the combined length of the ignition zone and cooling zone as described. Internal cross section dimensions for the cooling zone match those of the ignition zone.

The refractory-lined preheat zone of 10 feet has been found to conserve heat adequately within the tunnel and protect the operator from excessive heat if he is stationed at the inlet opening. Internal cross-section dimensions of the cooling zone also match those of the ignition zone.

Afterburner (Secondary Combustion Chamber)

To meet air pollution regulations, afterburners or secondary combustion chambers should be designed to raise the maximum volume of effluent from the ignition zone to at least 1,400°F for a minimum of 0.5 second. These conditions ensure essentially complete combustion of elemental carbon and most organic combustion contaminants in the primary effluent.

For turbulent mixing of the gaseous effluent with flames from natural gas- or oil-fired secondary burners, the cross section of the secondary combustion zone should be designed for average gas velocities of 20 to 30 fps and contain baffles or abrupt changes in gas flow. Secondary air ports should provide 100 percent theoretical combustion air for the combustible materials based upon a total processing time of 4 minutes per drum containing a maximum of 4 pounds of combustible materials.

Draft

Although draft is usually produced by a natural-draft stack or an induced-draft fan, the fan is preferred since it provides more nearly uniform draft under all phases of operation. Studies of various induced-draft fan systems show lowest costs for a system designed around a steel fan with heat slingers where combustion gases to the fan are cooled to 800°F or less by either air dilution or evaporative cooling. Cooling by air dilution is, however, preferred over evaporative cooling for several reasons. There is less corrosion of fan and ductwork with air dilution and there is very little deposit of fly ash and other combustion particles upon the blades of the induced-draft fan as commonly occurs when this fan follows a water spray chamber. In fact, with spray chambers, scraping deposits from the fan blades may be necessary every few days to keep the fan from becoming unbalanced.

A satisfactory air dilution system should consist of a chamber with a cross section such that a mixture of dilution air and combustion gases has an average velocity of 20 to 30 fps for a residence time of about 0.2 or 0.3 second. Turbulent mixing is further enhanced by adding baffles or right-angle bends. The induced-draft fan can be protected from excessively high temperatures by motor-driven dilution air dampers set to respond to a signal from a thermocouple located at the fan inlet.

Standards for Construction

Mechanical design and structural features of drum reclamation furnaces are discussed in general terms since most municipalities have their own specific building requirements. While these codes are written primarily to provide safe structures and prevent fires, designers should not hesitate to go beyond the codes in specifying refractories that will give a reasonably long service life and resist abrasion, erosion, spalling, and slagging.

The exterior walls of the furnaces are usually constructed of bonded brick or steel plate. These exterior walls are separated from the inner refractory lining by an airspace for cooling or by 2-1/2 inches or more of insulating materials with a service temperature of at least 2,000°F.

Furnace parts encountering the most severe heat, such as the single-batch chamber, the ignition zone of the continuous furnace, and the afterburner or secondary combustion chamber, should be lined with at least 9 inches of superduty firebrick or plastic refractory. Other parts of the continuous furnace under less severe heat conditions, preheat zone, cooling zone, and tunnel openings may be lined with 9 inches of high-heat-duty firebrick or ASTM Class 27 castable refractory.

Natural-draft stacks are usually constructed of 10-gage steel plate and lined with at least 2-1/2 inches of insulating castable with a minimum service temperature of 2,000°F.

Induced-draft fans may be constructed of low-carbon steel if gases are cooled by dilution air, but if water

sprays are used to cool exhaust gases, then the fan blades and the casing should be constructed of stainless steel or other corrosion- and heat-resistant metals.

Drag conveyors in continuous furnaces are driven by gearhead motors with bearings constructed of heat-resistant alloy or with bearings cooled by water.

Primary and secondary burners are usually nozzle mix type to provide luminous flame. Combustion air to the burners may be supplied by a single blower, but burner controls should allow for high turndown ratios.

Operation

Control of emissions from reclamation furnaces with afterburners or secondary combustion chambers still depends to a great extent upon the skill and vigilance of the operator. If visible emissions occur as a result of overloading the afterburner, the primary ignition burners should be cut back to reduce the burning rate.

While black exhaust smoke may indicate a lack of combustion air as well as an overloading of the afterburner, white smoke usually indicates insufficient temperature in the afterburner. White smoke can usually be reduced or eliminated by reducing the combustion air or by increasing the fuel consumption of the secondary burners.

Drum temperatures should be kept below 1,000°F to minimize drum warpage and scaling.

Illustrative Problem

Problem:

Design a continuous-tunnel-type furnace for processing 150 standard 55-gallon, steel, open-top drums per hour.

Given:

Combustible material attached to each drum varies from near zero to 4 pounds (typical of range of combustibles on most drums as received for processing).

All combustible material on the drums is considered to have a composition equivalent to that of US Grade 6 fuel oil.

Solution:

1. Primary ignition chamber:

a. Induced air through openings at 200 fpm and 60°F. Opening width = 26 in., height above conveyor = 36-1/2 in.; length = 30 in. Total opening area (2)(6.8 ft^2) = 13.6 ft^2. Induced air 13.6 ft^2 x 200 fpm = 2,720 scfm.

b. Size of ignition burners to raise effluent to 1,000°F.

Design ignition burners for most severe operation, that of negligible combustible per drum. Burners must raise temperature of drums to 900°F. From Table D1, Appendix D, density of air at 60°F and 14.7 psia is 0.076 lb/ft^3. Average specific heat of products of combustion is 0.26 Btu/lb-°F.

(1) Heat required to raise induced air from 60° to 1,000°F:

$$Q_1 = W_a \; C_{pa} \; (T_2 - T_a)$$

where

Q_1 = heat required, Btu/hr

W_a = weight of air, lb/hr

C_{pa} = average specific heat over temperature range

T_2 = final temperature, °F

T_a = ambient air temperature, °F

$$Q_1 = (2,720 \text{ scfm})\left(\frac{60 \text{ min}}{\text{hr}}\right)\left(\frac{0.076 \text{ lb}}{\text{ft}^3}\right)(0.26 \text{ Btu/lb-°F})$$

(1,000°F - 60°F) = 3,030,000 Btu/hr

(2) Heat required to raise temperature of drums from 60° to 900°F:

The specific heat of steel for this temperature range is 0.12 Btu/lb-°F.

$$Q_2 = W_d \; C_{pd} \; (T_2 - T_1)$$

where

Q_2 = heat required, Btu/hr

W_d = weight of drums, lb/hr

C_{pd} = specific heat of steel, Btu/lb-°F

T_2 = final temperature

T_1 = initial temperature

$$Q_2 = \left(\frac{150 \text{ drums}}{\text{hr}}\right)\left(\frac{55 \text{ lb}}{\text{drum}}\right)\left(0.12 \frac{\text{Btu}}{\text{lb-°F}}\right)(900°F - 60°F)$$

$$= 833,000 \text{ Btu/hr}$$

(3) Total heat required in ignition zone:

Assume heat losses through radiation, storage, and so on are 10 percent of total gross heat input.

$$\frac{3,030,000 \text{ Btu/hr} + 833,000 \text{ Btu/hr}}{0.90} = 4,300,000 \text{ Btu/hr}$$

(4) Natural-gas capacity of primary burners:

From Table D7, Appendix D, the calorific value of 1 scf natural gas with 20 percent excess air is 736.2 Btu at 1,000°F.

$$\text{Total capacity} = \frac{4,300,000 \text{ Btu/hr}}{736.2 \text{ Btu/scf}} = 5,830 \text{ scfh}$$

(5) Individual burner capacity:

Install eight rows of three burners each (four rows on each side of the zone)

$$\text{Burner capacity} = \frac{5,830 \text{ scfh}}{24} = 243 \text{ scfh}$$

c. Excess primary combustion air:

Assume all air for burning materials on drums is induced through tunnel openings (including air supplied by air curtains).

(1) Maximum design burning rate:

$$\left(\frac{150 \text{ drums}}{\text{hr}}\right)\left(\frac{4 \text{ lb}}{\text{drum}}\right) = 600 \text{ lb/hr}$$

$$= 10 \text{ lb/min}$$

(2) Total combustion air available through tunnel openings:

$$\text{Air} = \frac{2,720 \text{ scfm}}{10 \text{ lb/min}} = 272 \text{ scf/lb}$$

From Table D6, Appendix D, 1 lb US Grade 6 fuel oil requires 177 scf air 40 percent saturated at 60°F.

$$\% \text{ excess air available} = \frac{272 \text{ scf} - 177 \text{ scf}}{177 \text{ scf}}$$

$$= 54\%$$

d. Average gas temperature in ignition zone when burning a maximum of 4 pounds combustibles per drum:

Assume first rows of burners on opposite sides of zone are operating at 1 million Btu/hr (910 scfh) to ignite combustibles on drums. Design gas burners to operate with 20 percent excess air. Assume radiation, storage, and other heat losses are 35 percent of gross heat input at furnace temperatures near 2,000°F. From Table D5, Appendix D, the gross heat of combustion of 1 pound US Grade 6 fuel oil is 18,000 Btu.

(1) Gross heat:

Primary burner = 1 million Btu/hr

Combustibles

$$\left(\frac{600 \text{ lb}}{\text{hr}}\right)\left(18,000 \frac{\text{Btu}}{\text{lb}}\right) = 10,800,000 \text{ Btu/hr}$$

Total = 11,800,000 Btu/hr

(2) Heat losses, radiation, storage, and so on:

$$(0.35)(11,800,000 \text{ Btu/hr}) = 4,130,000 \text{ Btu/hr}$$

(3) Evaporation of moisture contained in drums:

Assume an average of 0.5 lb water per drum. The heat of vaporization of 1 pound of water at 60°F and 14.7 psia is 1,060 Btu.

$$\left(0.5 \frac{\text{lb}}{\text{drum}}\right)\left(\frac{150 \text{ drums}}{\text{hr}}\right)\left(\frac{1,060 \text{ Btu}}{\text{lb}}\right) =$$

79,500 Btu/hr

(4) Evaporation of water formed by combustion:

From Tables D7 and D6, Appendix D, 0.099 lb water is formed by burning 1 scf natural gas with 20 percent excess air while 0.91 lb water is formed from burning 1 lb US Grade 6 fuel oil with 54 percent excess air.

Natural gas:

$$(910 \text{ scfh})\left(\frac{0.099 \text{ lb } H_2O}{\text{scf}}\right)\left(1,060 \frac{\text{Btu}}{\text{lb}}\right) = 95,500 \text{ Btu/hr}$$

Combustibles:

$$\left(\frac{600 \text{ lb}}{\text{hr}}\right)\left(\frac{0.91 \text{ lb } H_2O}{\text{lb}}\right)\left(1,060 \frac{\text{Btu}}{\text{lb}}\right) = 578,000 \text{ Btu/hr}$$

Total = 673,500 Btu/hr

(5) Total heat losses:

(2) + (3) + (4) = 4,883,000 Btu/hr

(6) Net heat available to raise temperature of products of combustion:

11,800,000 Btu/hr - 4,883,000 Btu/hr

= 6,917,000 Btu/hr

(7) Weight of products of combustion:

From Tables D7 and D6, Appendix D, there is 0.999 lb products of combustion from 1 scf hatural gas with 20 percent excess air and there is 21.71 lb products of combustion from 1 pound US Grade 6 fuel oil with 54 percent excess air.

(910 scfh)(0.999 lb/scf) = 909 lb/hr

$\left(600 \frac{lb}{hr}\right)\left(\frac{21.71 \text{ lb}}{lb}\right)$ = 13,000 lb/hr

Total = 13,909 lb/hr

(8) Average gas temperature:

Average specific heat of products of combustion (equivalent to air) is taken to be 0.26 Btu/lb-°F for the given temperature range.

$$\Delta T = \frac{Q_3}{W_t C_{pc}}$$

where

ΔT = temperature rise, °F above 60°F

Q_3 = heat available, Btu/hr

W_t = weight of products of combustion, lb/hr

C_{pc} = average specific heat, Btu/lb-°F

$$\Delta T = \frac{6,917,000 \text{ Btu/hr}}{(13,909 \text{ lb/hr})\left(0.26 \frac{Btu}{lb\text{-}°F}\right)} = 1,910°F$$

Final Temp = 60 + 1,910 = 1,970°F

e. Volume of products of combustion at 60°F

(1) With negligible combustibles on drums:

Induced air:

(2,720 scfm)(60 min/hr) = 163,000 scfh

Primary burners:

(5,830 scfh)(13.53 scf/scf) = 79,000 scfh

Total = 242,000 scfh

4,040 scfm

67.3 scfs

(2) With 4 pounds combustibles per drum

Assume primary burners are operating at 910 scfh. From Table D6, Appendix D, there is 281.9 ft^3 products of combustion from 1 pound US Grade 6 fuel oil with 54 percent excess air.

Combustibles:

(600 lb/hr)(281.9 ft^3/lb) = 169,000 scfh

Primary burners:

(910 scfh)(13.53 scf/scf) = 12,300 scfh

Total = 181,300 scfh

= 3,020 scfm

= 50.4 scfs

The most severe operating conditions exist, therefore, in the ignition chamber when drums with negligible combustible material are processed.

f. Volume of ignition zone:

Assume a heat release factor of 22,000 Btu/hr-ft^3, which is similar to heat release factors for oil-fired furnace fireboxes operating at less than 1,800°F. Assume drums contain negligible combustible materials.

$$\text{Volume} = \frac{(5,830 \text{ scfh})(1,100 \text{ Btu/scf})}{22,000 \text{ Btu/hr-ft}^3}$$

$$= 292 \text{ ft}^3$$

g. Length of ignition zone:

Assume width = 36 in.; height = 84 in., including the conveyor

$$\text{Length} = \frac{\text{volume}}{(\text{height})(\text{width})} = \frac{292 \text{ ft}^3}{(3 \text{ ft})(7 \text{ ft})} = 14 \text{ ft}$$

h. Cooling zone length:

Assume width = 36 in., height = 84 in., including the conveyor. Design ignition zone and cooling zone for a total residence time of 4

min. Assume a drum spacing of 29 in. (5 in. between drums). Internal cross-sectional dimensions match those of ignition zone.

$$\text{Conveyor speed} = \left(\frac{150 \text{ drums}}{\text{hr}}\right)\left(\frac{1 \text{ hr}}{60 \text{ min}}\right)\left(\frac{2.41 \text{ ft}}{\text{drum}}\right)$$

$$= 6 \text{ fpm}$$

Length of ignition and cooling zones

Total length = (6 ft/min)(4 min) = 24 ft

Cooling zone length, 24 ft - 14 ft = 10 ft

i. Preheat zone length:

Design this zone to minimize radiation losses and to protect operator. Internal cross-sectional dimensions match those of ignition zone.

Design preheat zone length = 10 ft

Evaluation of existing design shows that a preheat zone length of 10 ft will be adequate.

2. Secondary-combustion chamber (afterburner):

a. Design gas burners for most severe operation (drums contain negligible combustibles). Afterburner will raise temperature of products of combustion from ignition zone from 1,000° to 1,400°F.

(1) Weight of products of combustion:

From ignition zone:

Induced air:

$$(2,720 \text{ scfm})\left(0.076 \frac{\text{lb}}{\text{ft}^3}\right)\left(\frac{60 \text{ min}}{\text{hr}}\right) = 12,400 \text{ lb/hr}$$

Natural gas:

$$(5,830 \text{ scfh})\frac{(0.999 \text{ lb})}{\text{scf}} = 5,870 \text{ lb/hr}$$

Total = 18,270 lb/hr

(2) Heat required to raise temperature of products of combustion to 1,400°F:

Average specific heat of products of combustion is 0.26 Btu/lb-°F over the given temperature range.

$$Q_3 = W_t C_{pc} (T_2 - T_1)$$

where

T_2 = initial temperature, °F

T_1 = final temperature, °F

$$Q_3 = \left(18,270 \frac{\text{lb}}{\text{hr}}\right)\left(\frac{0.26 \text{ Btu}}{\text{lb-°F}}\right)(1,400°\text{F} - 1,000°\text{F})$$

$$= 1,900,000 \text{ Btu/hr}$$

(3) Total heat required in afterburner:

Assume heat losses by radiation, convection, and so on are 10 percent of gross heat supply at 1,400°F

$$\text{Total heat} = \frac{1,900,000 \text{ Btu/hr}}{0.90} = 2,110,000 \text{ Btu/hr}$$

(4) Total capacity of secondary burners:

From Table D7, Appendix D, the calorific value of 1 scf natural gas is 615.4 Btu at 1,400°F with 20 percent excess air.

$$\text{Natural gas} = \frac{2,110,000 \text{ Btu/hr}}{615.4 \text{ Btu/scf}} = 3,430 \text{ scfh}$$

(5) Individual secondary burner capacity:

Install four burners--two on each side of the horizontal section.

$$\text{Capacity of burner} = \frac{3,430 \text{ scfh}}{4 \text{ burners}} = 856 \text{ scfh}$$

b. Cross-sectional area:

Design afterburner for a cross-section velocity of 30 fps maximum at 1,400°F. From Table in Appendix, there are 13.53 scf products of combustion from 1 scf natural gas with 20 percent excess air.

(1) Volume of products of combustion when drums are burned with negligible combustibles:

Induced air:

$$(2,720 \text{ scfm})\left(\frac{60 \text{ min}}{\text{hr}}\right) = 163,000 \text{ scfh}$$

Primary burners:

$$(5,830 \text{ scfh})\left(\frac{13.53 \text{ scf}}{\text{scf}}\right) = 79,000 \text{ scfh}$$

Secondary burners:

$$(3,430\ \text{scfh})\left(\frac{13.53\ \text{scf}}{\text{scf}}\right) = 46,500\ \text{scfh}$$

Total = 288,500 scfh
= 4,810 scfm
= 80.2 scfs

(2) Volume of products of combustion through afterburner when drums are burned with 4 lb combustibles:

Assume primary burners are operating at 910 scfh and that secondary burners operate at 20 percent full capacity. Assume afterburner outlet temperature is 2,100°F.

Products of combustion:

Combustibles:

(600 lb/hr)(281.9 cf/lb) = 169,000 scfh

Primary burners:

$$(910\ \text{scfh})\left(\frac{13.53\ \text{scf}}{\text{scf}}\right) = 12,300\ \text{scfh}$$

Secondary burners:

$$(0.20)(3,430\ \text{scfh})\left(\frac{13.53\ \text{scf}}{\text{scf}}\right) = 9,300\ \text{scfh}$$

Total = 190,600 scfh
= 3,180 scfm
= 53.0 scfs

(3) Internal cross-sectional area and dimensions:

$$\text{Area} = \left(\frac{80.2\ \text{scfs}}{30\ \text{fps}}\right)\left(\frac{1,860°\text{R}}{520°\text{R}}\right) = 9.6\ \text{ft}^2$$

Dimensions = 3 ft 2 in. wide x 3 ft high

c. Length of afterburner:

Design for a minimum residence time of 0.5 second.

Length = (30 fps)(0.5 second) = 15 ft

d. Afterburner arrangement:

Design for 2 right-angle bends and add dilution air at third right-angle bend.

e. Secondary air port

Design a secondary air port to supply up to 100 percent theoretical air for drums containing 4 lb combustibles. From Table D6, Appendix D, 177 scf air is required to burn 1 pound of US Grade 6 fuel oil.

(1) Volume of combustion air at 60°F:

$$(600\ \text{lb/hr})\left(177\ \frac{\text{scf}}{\text{lb}}\right) = 106,000\ \text{scfh}$$
$$1,770\ \text{scfm}$$

(2) Pressure drop through opening at end of tunnel:

Drum cross-sectional area:

24 in. in diameter x 34 in. high = 5.7 ft^2

$$\text{Inlet velocity} = \frac{2,720\ \text{scfm}}{(2)(\text{opening area - drum area})}$$

$$\text{Inlet velocity} = \frac{2,720\ \text{scfm}}{(2)(6.8\ \text{ft}^2 - 5.7\ \text{ft}^2)} = 1,190\ \text{fpm}$$

Total pressure behind opening:

$$TP = VP + SP$$

where

TP = total pressure, in. WC

SP = static pressure, in. WC

VP = velocity pressure, in. WC

From Table D8, Appendix D, velocity pressure is 0.090 in. WC for a velocity of 1,190 fpm at 60°F. Assume static pressure drop through sharp-edge orifice opening is 0.5 VP and negligible friction loss in a 30-in. length of opening.

TP = 0.090 in. WC + 0.5 (0.090 in. WC)
= 0.135 in. WC

(3) Pressure drop through preheat zone:

Cross-sectional area for air flow with drums upon conveyor. Assume half of total combustion air through preheat zone.

Area = 21 ft^2 - 5.7 ft^2 = 15.3 ft^2

$$\text{Velocity} = \frac{(0.5)(2,720\ \text{scfm})}{15.3\ \text{ft}^2} = 88.5\ \text{fpm}$$

Because of low velocity, the pressure drop is negligible.

(4) Pressure drop through ignition zone:

Assume friction is negligible and pressure drop is 1 VP for 90-degree bend (into afterburner).

Assume flow conditions for negligible combustibles on drums. Cross section inlet duct of afterburner 9.6 ft^2.

Induced air: = 2,720 scfm

Primary burners:

$$(5,830\ \text{scfh})\frac{(\text{hr})}{60\ \text{min}}\frac{(13.53\ \text{scf})}{\text{scf}} = 1,320\ \text{scfm}$$

Total = 4,040 scfm

= 67.4 scfs

Average velocity into afterburner at 1,000°F:

$$\text{Velocity} = \left(\frac{67.4\ \text{scfs}}{9.6\ \text{ft}^2}\right)\left(\frac{1,460°\text{R}}{520°\text{R}}\right) = 19.7\ \text{fps}$$

VP = 0.032 in. WC at 1,000°F.

Pressure drop through one half ignition zone = 0.032 in. WC

(5) Total pressure at inlet to afterburner (behind secondary air port):

Tunnel opening	=	0.045 in. WC
Preheat zone	=	0
Ignition zone	=	0.032 in. WC
Total static pressure	=	0.077 in. WC

TP = VP + SP

TP = 0.032 + 0.077 = 0.109 in WC

(6) Velocity through secondary air port:

Assume 0.5 VP static pressure drop through sharp-edge opening of secondary port.

TP = VP + SP

0.109 in. WC = VP + 0.5 VP

1.5 VP = 0.109 in. WC

VP = 0.073 in. WC

From Table D8 in Appendix D:

Velocity = 1,070 fpm at 60°F

(7) Secondary air port area:

$$\text{Minimum area} = \frac{1,770\ \text{scfm}}{1,070\ \text{fpm}} = 1.65\ \text{ft}^2$$

Install oversize secondary port with area = 2 ft^2

3. Dimensions of dilution air chamber:

Design dilution air port to reduce temperature of products of combustion from afterburner to 700°F for safe fan operation.

a. Dilution air required to lower products of combustion from 1,400° to 700°F:

Density of products of combustion 0.076 lb/scf at 14.7 psia and 60°F

$$W_{pc}\ C_{pc}\ (T_2 - T_1) = W_a\ C_{pa}\ (T_1 - T_a)$$

$$(4,810\ \text{scfm})\left(\frac{0.076\ \text{lb}}{\text{scf}}\right)\left(\frac{0.26\ \text{Btu}}{\text{lb-°F}}\right)(1,400°\text{F} - 700°\text{F})$$

$$= W_a\ \frac{(0.26\ \text{Btu})}{\text{lb-°F}}\ (700°\text{F} - 60°\text{F})$$

W_a = 400 lb/min

$$\text{Dilution air} = \frac{400\ \text{lb/min}}{0.076\ \text{lb/scf}} = 5,260\ \text{scfm}$$

b. Dilution air required to lower products of combustion from 2,100° to 700°F;

$$(3,180\ \text{scfm})\left(\frac{0.076\ \text{lb}}{\text{scf}}\right)\left(\frac{0.26\ \text{Btu}}{\text{lb-°F}}\right)(2,100°\text{F} - 700°\text{F})$$

$$= W_a\ \frac{(0.26\ \text{Btu})}{\text{lb-°F}}\ (700°\text{F} - 60°\text{F})$$

W_a = 529 lb/hr

$$\text{Dilution air} = \frac{529\ \text{lb/hr}}{0.076\ \text{lb/scf}} = 6,950\ \text{scfm}$$

e. Cross section of dilution air chamber:

Design for a velocity of 30 fps at 700°F to ensure turbulent flow for good mixing.

Total flow to fan at 700°F:

Condition 1: (no combustibles on drums, maximum primary burner capacity)

$$(4,810 \text{ scfm} + 5,260 \text{ scfm}) \frac{(1,360°R)}{520°R} = 26,400 \text{ cfm}$$

Condition 2: (4 lb combustibles per drum, primary burners 910 scfm)

$$(6,950 \text{ scfm} + 3,180 \text{ scfm}) \frac{(1,360°R)}{520°R} = 26,500 \text{ cfm}$$

$$\text{Maximum cross-sectional area} = \frac{26,500 \text{ cfm}}{(30 \text{ fps})\left(\frac{60 \text{ sec}}{\text{min}}\right)}$$

$$= 14.7 \text{ ft}^2$$

Cross-sectional dimensions 4 ft 8 in. wide x 3 ft 2 in. high

d. Length of dilution air chamber:

Design for a residence time of 0.3 sec

Length = (30 fps)(0.3 sec) = 9 ft

4. Static pressure drop through system:

Design system with induced-draft fan mounted at ground level and a vertical stack on the fan outlet 50 in. in diameter x 20 ft high. The 50-in. diameter will keep stack velocity near 30 fps through afterburner.

a. Static pressure at afterburner inlet = 0.077 in. WC, see item (5), page 492.

b. Static pressure drop through afterburner:

(1) Velocity pressure at 30 fps and 1,000°F:

Assume combustion products are equivalent in composition to air.

$$V = 2.9\sqrt{th}$$*

where

V = gas velocity, fps

t = absolute temperature, °R

h = velocity pressure (head), in. WC

$$h = \left(\frac{V}{2.9}\right)^2 \left(\frac{1}{t}\right)$$

$$h = \left(\frac{30 \text{ fps}}{2.9}\right)^2 \left(\frac{1}{1,460°R}\right) = 0.073 \text{ in. WC}$$

(2) Pressure drop from contraction at inlet to afterburner:

Assume 0.5 VP drop for abrupt contraction

$$(0.5)\left(0.07 \frac{\text{in. WC}}{\text{VP}}\right) = 0.035 \text{ in. WC}$$

(3) Pressure drop for three right-angle bends:

Assume 1 VP for each right-angle bend.

$$(3 \text{ VP})\left(\frac{0.07 \text{ in. WC}}{\text{VP}}\right) = 0.21 \text{ in. WC}$$

(4) Friction loss through 15 ft of ductwork having dimensions 3 ft 2 in. wide x 3 ft high.

$$f = \frac{0.002 \, h \, v^2}{mt}$$†

where

f = friction, in. WC

h = duct length, ft

v = gas velocity, fps

t = absolute temperature, °R

m = hydraulic radius

$$m = \frac{\text{cross-sectional area of duct, ft}^2}{\text{perimeter of duct, ft}}$$

$$f = \frac{(0.002)(15 \text{ ft})(30 \text{ fps})^2}{(0.778 \text{ ft})(1,460°R)} = 0.024 \text{ in. WC}$$

(5) Total drop through afterburner:

(2) + (3) + (4) = 0.269 in. WC

*Research-Cottrell, Inc.

†Griswold, 1946.

c. Static pressure drop through dilution air chamber having dimensions 4 ft 8 in. wide x 3 ft 2 in. high.

(1) Friction loss through ductwork at 700°F:

$$f = \frac{0.002\ h\ v^2}{mt}$$

$$f = \frac{(0.002)(9)(30)^2}{(0.945)(1,160)} = 0.015 \text{ in. WC}$$

d. Static pressure drop through 50-in.-diameter x 20-ft-high stack on discharge side of fan:

$$\text{Stack velocity at 700°F} = \frac{26,500 \text{ cfm}}{13.64 \text{ ft}^2}$$

$$= 1,940 \text{ fpm}$$

$$= 32.4 \text{ fps}$$

$$f = \frac{0.002\ h\ v^2}{mt}$$

where

$$m = \frac{D}{4} = \frac{4.16}{4} = 1.04 \text{ ft}$$

$$f = \frac{0.002\ (20 \text{ ft})(32.4 \text{ fps})^2}{(1.04 \text{ ft})(1,160°F)} = 0.035 \text{ in. WC}$$

e. Total static pressure drop through system:

Tunnel	=	0.077 in. WC
Afterburner	=	0.269 in. WC
Dilution air chamber	=	0.015 in. WC
Fan outlet duct	=	0.035 in. WC
Total static pressure	=	0.396 in. WC

5. Dilution air port size:

a. Total pressure behind dilution air port:

Velocity pressure 30 fps at 700°F, VP = 0.10 in. WC

$$TP = VP + SP$$

$$TP = 0.10 + (0.077 + 0.269) = 0.446 \text{ in. WC}$$

b. Inlet velocity through dilution air port:

Assume 0.5 VP static pressure drop for sharp-edge orifice air port.

$$TP = VP + SP$$

0.446 in. WC = VP + 0.5 VP; VP = 0.298 in. WC at 60°F

Inlet velocity = 2,165 fpm

c. Size of dilution air port:

$$\text{Minimum size} = \frac{6,950 \text{ scfm}}{2,165 \text{ fpm}} = 3.21 \text{ ft}^2$$

Select a port with area = 4 ft^2

6. System static pressure curve development at 700°F:

$$SP_2 = SP_1\left(\frac{cfm_2}{cfm_1}\right)^2$$

where

SP_2 = static pressure, final conditions, in. WC

SP_1 = static pressure, initial conditions, in. WC

cfm_2 = gas flow, final conditions, cfm

cfm_1 = gas flow, initial conditions, cfm

Assume cfm_2 = 30,000

$$SP_2 = (0.396)\left(\frac{30,000}{26,500}\right)^2 = 0.507 \text{ in. WC}$$

Assume cfm_2 = 20,000

$$SP_2 = (0.396)\left(\frac{20,000}{26,500}\right)^2 = 0.226 \text{ in. WC}$$

7. Fan specifications:

Select a fan that will deliver about 26,500 cfm at 700°F and 0.4 in. WC static pressure.

a. Fan performance at 60°F operation:

329 rpm	60°F	1.0 in. WC 25,245 cfm 12.66 bhp
0.75 in. WC 26,775 cfm 14.9 bhp		1.25 in. WC 22,185 cfm 10.79 bhp

b. Calculate points for 700°F fan performance curve:

With rpm and cfm held constant, static pressure and bhp vary directly with gas density or inversely with absolute temperature.

$$\text{Correction ratio} = \frac{520}{1,160} = 0.448$$

329 rpm 700°F	0.448 in. WC 25,245 cfm 5.7 bhp
0.336 in. WC 26,775 cfm 6.7 bhp	0.57 in. WC 22,185 cfm 4.9 bhp

c. Operating point at 700°F:

The intersection of the 700°F system curve with the 700°F fan curve, as shown in Figure 347, yields data indicating that this system will handle a volume of 26,000 cfm at 0.38 in. WC at 700°F. The fan will operate at 329 rpm with 6.3 bhp.

d. Fan Selection:

Select a 20-hp motor to drive fan since about 14 bhp will be required when starting from a cold lightoff.

Select a fan with a capacity and static pressure 10 to 20 percent in excess of the operating point shown in Figure 347 as a safety factor for overload capability.

WIRE RECLAMATION

Scrap-insulated electrical wire from construction sites and factories, and worn-out insulated wire from utility companies and other industrial operations constitute the bulk of the insulated wire processed for the recovery of copper scrap. Several methods are employed for removing insulation from the copper core. The method selected depends not only upon the size of the wire but also upon the composition of the insulation. This process differs from other reclamation in that the combustible content of the charge is always more than 10 percent by weight and usually exceeds 20 percent. This one distinguishing feature is reflected in the specialized designs of combustion equipment used exclusively for reclaiming electrical insulated wire.

DESCRIPTION OF THE PROCESS

Inorganic insulating materials such as fiber glass and ceramics cannot be burned and must be re-

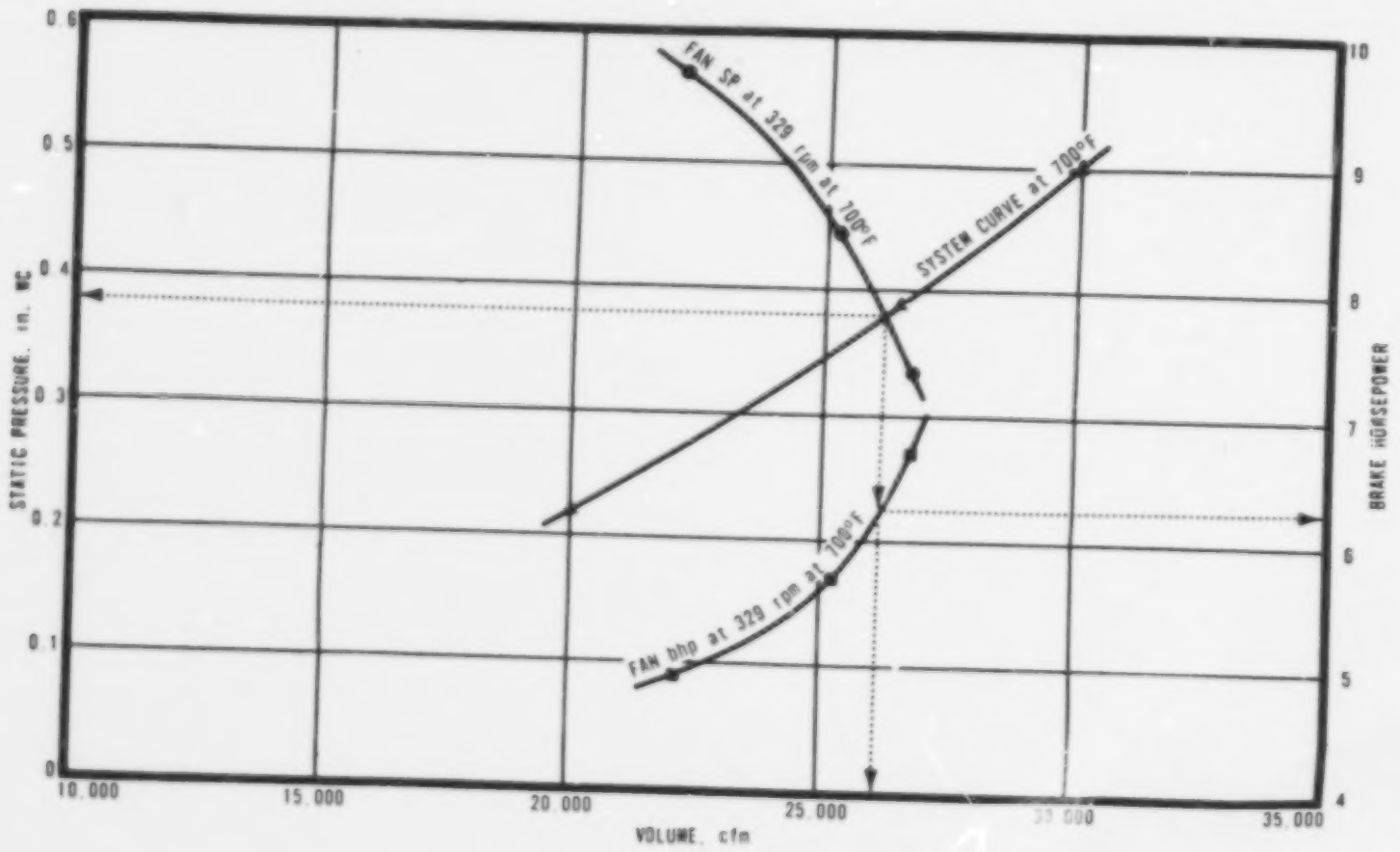


Figure 347. Performance curve of 700°F fan.

moved mechanically. Much insulation is composed of organic compounds that will burn; however, not all combustible insulation is removed by this method. Because of excessive oxidation of copper, wire smaller than 14 gage is not burned; it is actually thrown away because of the lack of a satisfactory economical method of removing insulation. On the other hand, communication cable, 1 inch in diameter or greater, is usually cut into pieces about 1 foot long and the insulation is hand stripped. This method has proved more satisfactory than burning since the copper scrap is clean and free of the surface oxides and foreign matter associated with the burning process.

Wire of the intermediate sizes was formerly burned in the open or in single-chamber furnaces in Los Angeles County. When burned in the open, the wire was spread in thin piles less than 1 foot high and sprinkled with some type of petroleum distillate to initiate combustion. The combustible content of the wire was usually sufficient to maintain active burning until the insulation was consumed.

In a single-chamber furnace, the wire was ignited with a hand torch or a gas burner mounted through the side of the chamber. After ignition, the burning process was also self-sustaining in this equipment. After burning was complete, the wire was allowed to cool and the char adhering to the bare copper wire was removed by rapping or by high velocity jets of water.

DESCRIPTION OF THE CHARGE

A great variety of materials composes the combustible insulation: Rubber, paper, cotton, silk, and plastics such as polyethylene and polyvinyl chloride. Moreover, the wire itself may have a baked-on coating of plastics, paint, or varnish.

As received for burning, the total combustible content of the insulated wire may vary widely from several percent to over 50 percent by weight. Most commercial wire contains from 20 to 35 percent insulation.

THE AIR POLLUTION PROBLEM

Burning in the open is accompanied by copious quantities of dense smoke, disagreeable odors, inorganic materials, and oxygenated hydrocarbons. Burning in single-chamber incinerators produces somewhat less smoke, odors, and other air contaminants than open burning does, since combustion air can be regulated. Results of Source Tests C-624-1 and C-543-1, given in Table 136, are considered representative of emissions from single-chamber incinerators since these tests were conducted on two multiple-chamber retort furnaces operating without their secondary burners. In these two tests, particulate-matter concentrations in the stack effluent averaged 356 and 190 pounds per ton of insulation burned, respectively. Smoke emissions were a constant 100 percent black during one entire test and varied continuously from 20 to 90 percent gray during the other test.

AIR POLLUTION CONTROL EQUIPMENT

The only practical industrial equipment available today for controlling emissions from single-chamber insulation-burning incinerators is an afterburner or secondary combustion chamber. For the design of afterburners see general information in the first part of Chapter 5.

Final selection of equipment designed to burn insulation and control emissions is based upon considerations such as space limitations, charge composition, process conditions, maintenance, capital investment, and operating expenses. To design an effective afterburner or secondary combustion chamber, one must determine or initially design the size and appurtenances of the primary ignition chamber. Recommended values for designing a complete furnace are presented in Table 137.

During recent years, reclamation of wire coated with PVC or other plastics containing inorganic filler of organic oxides or clay has been on the increase. During combustion of the wire, the inorganic materials are volatilized in the form of fine particles. These particles are entrained by the combustion products from the primary chamber and pass through the secondary combustion zone without burning. The concentration of these inorganic particles can result in emissions of excessive opacity. If such a problem develops, secondary combustion must be followed by a baghouse or possibly a venturi scrubber operating at a high pressure drop. Designs for baghouses or venturi scrubbers are discussed in Chapter 4.

Primary Ignition Chamber

The size of the primary chamber is based upon the density, volume, and burning rate of a typical charge. There is nothing critical about the shape of this chamber. Any reasonable box shape will suffice for a given batch charge provided additional space is provided to facilitate loading and unloading.

Control of primary combustion air is critical since not only must high temperatures be prevented from excessively oxidizing copper, but also the burning rate must be restricted to prevent overloading of the secondary-combustion chamber. Precise control of combustion air is important because it makes possible the use of an afterburner or secondary combustion chamber of reasonable size.

Table 136. SOURCE TESTS: WIRE RECLAMATION WITH MULTIPLE-CHAMBER RETORT FURNACES

Test No.	C-624-1	C-624-2	C-543-1	C-543-3	C-696
Operation of secondary burners	Burners off	Burners on	Burners off	Burners on	Burners on
Incinerator number	1	1	2	2	3
Charge composition	5/8 in. OD typical rubber-covered wire	5/8 in. OD typical rubber-covered wire	3/8 to 5/8 in. OD cotton-rubber plastic-covered wire	3/8 to 5/8 in. OD cotton-rubber plastic-covered wire	1/4 to 3/4 in. OD cotton-rubber-covered wire
Test duration, min	24	40	20	17	83
Charge weight, lb	220	233	100	147	960
Combustibles in charge, wt %	35	16	19	34.7	22.6
Ash in charge, % by wt	6	6	4	4	4
Combustion rate, lb/hr	195	56	57	180	160
Smoke opacities, %	Constant 100% black	0 to 25% white	20 to 90% gray	0 to 10% white	0 to 10% white
Particulates, gr/scf at 12% CO_2	29.0	0.26	3.5	0.32	0.16
lb particulates/ton combustible	356	35	190	21	20
Mixing chamber, °F	780	1,880[a]	300 est	1,880[a]	2,000[a]
Mixing chamber velocity, fpm	11	45.0	9.1	31.2	42.5
Aldehydes, ppm	105	5	9 to 36	4	Not available
Hydrocarbons, ppm	640	8	9 to 31	8	Not available
Nitrogen oxides, ppm	11	25	2.9 to 8.5	10.4	Not available
Sulfur compounds as SO_2, % by vol	0.012	0.0039	0.0014	0.0027	0.0094

[a]Temperature measured by chromel alumel thermocouple in flame contact.

To minimize the size of the afterburner or secondary combustion chamber, the primary chamber should be equipped with a tightly fitting air port and a side swing charge door. Although the primary air ports are designed to supply 100 percent excess theoretical air for operating flexibility, air leakage around the edges of the charge door and air ports in most cases supplies the required combustion air so that primary air ports are usually kept in a closed position. For design purposes, indraft velocities through the primary air ports should average 900 fpm, equivalent to a velocity pressure of 0.05 inch of water column.

Because the combustion process is self-sustaining, only a small-capacity primary-chamber burner, that is, one capable of 50,000 Btu per hour, is required for igniting the refuse. After ignition, emissions from the primary chamber usually consist of smoke and gases without flame and vary in temperature from 900° to 1,300°F upon entering the secondary combustion chamber.

Ducts or ports connecting the secondary chamber or afterburner with the primary chamber are designed for a velocity of 30 fps or less, at maximum combustion rates, to prevent excessive restriction to the flow of gases. Undue restriction may result in emission of smoke and flames from the primary air ports or around the charging door.

Secondary Combustion

As the gaseous emissions enter the secondary combustion chamber or afterburner, combustion air is added (up to 100 percent of theoretical) through the secondary air port. The effluent then passes through the luminous flames of the secondary burner, which is designed to attain an average gas temperature of 1,600°F. This temperature is maintained for a minimum of 0.5 second with average gas velocities of 25 to 40 fps. Baffles and abrupt changes in direction provide additional turbulence for mixing burner flames with the air and combustion gases.

Secondary combustion air ports are also designed for 900-fpm inlet velocities. Additional air may be induced through a port in the base of the stack to cool the stack gases and protect the refractory lining of the stack.

Emissions

Table 136 shows significant reductions of particulates, aldehydes, hydrocarbons, and smoke through secondary combustion. Source tests C-624 and C-543 were conducted on two multiple-chamber retort furnaces with and without their secondary burners in operation. Tests conducted on a third furnace with secondary combustion show a particulate discharge of only 20 pounds per ton of insulation burned. This lower rate is the result of having a high temperature of 2,000°F in the secondary chamber and a long residence time of 0.55 second.

Not all combustible insulation can be burned in multiple-chamber retort furnaces without producing emissions of excessive opacity. Clays and inorganic oxides used as fillers in polyvinyl chloride

Table 137. EQUIPMENT DESIGN FACTORS

Item	Recommended value and units	Allowable deviation
Gas velocities		
Primary-chamber outlet duct or port at 1,300°F	30 ft/sec	± 20%
Afterburner or secondary mixing chamber at 1,600°F	30 ft/sec	± 20%
Extended secondary mixing chamber curtain wall port tunnel at 1,600°F	30 ft/sec	± 20%
Stack	30 ft/sec	± 20%
Residence time		
Maximum flow at 1,600°F	0.50 sec	± 20%
Combustion air		
Air requirements		
Primary air	100% excess	
Secondary air	100% theoretical	
Combustion air distribution		
Primary ports	66%	
Secondary ports	35%	
Airport inlet velocity		
Primary airport	900 fpm or 0.051 in. WC	
Secondary airport	900 fpm or 0.051 in. WC	
Auxiliary burners		
Primary burner or torch capacity	50 cfh	
Secondary burner capacity	15,600 Btu/lb combustible	
Draft requirements		
Ignition chamber	0.05 to 0.10 in. WC	
Outlet from secondary chamber (afterburner)	0.20 in. WC	

and other insulation plastics produce objectionable emissions consisting of micron and submicron, noncombustible, inorganic particles of clay and metallic oxides that are vaporized as the plastic burns.

Draft

Draft is usually produced by a natural-draft stack that can be designed by standard calculations. Regardless of the method employed to generate draft, at least 0.05 inch water column negative static pressure should be available in the ignition chamber, and a minimum of 0.20 inch water column at the outlet from the secondary combustion chamber.

Equipment Arrangement

Batch equipment is usually constructed in one of two configurations--a dual structure consisting of a primary chamber venting through an afterburner or a single structure containing a primary chamber and one or two secondary combustion chambers arranged similarly to a multiple-chamber incinerator.

A typical multiple-chamber retort wire reclamation furnace, shown in Figure 348, differs from a multiple-chamber retort incinerator in that the primary chamber has no grates and the charge rests upon the floor of the chamber. To increase the residence time in the secondary combustion zone, the curtain wall port is extended across the bottom of the combustion chamber, forming a tunnel.

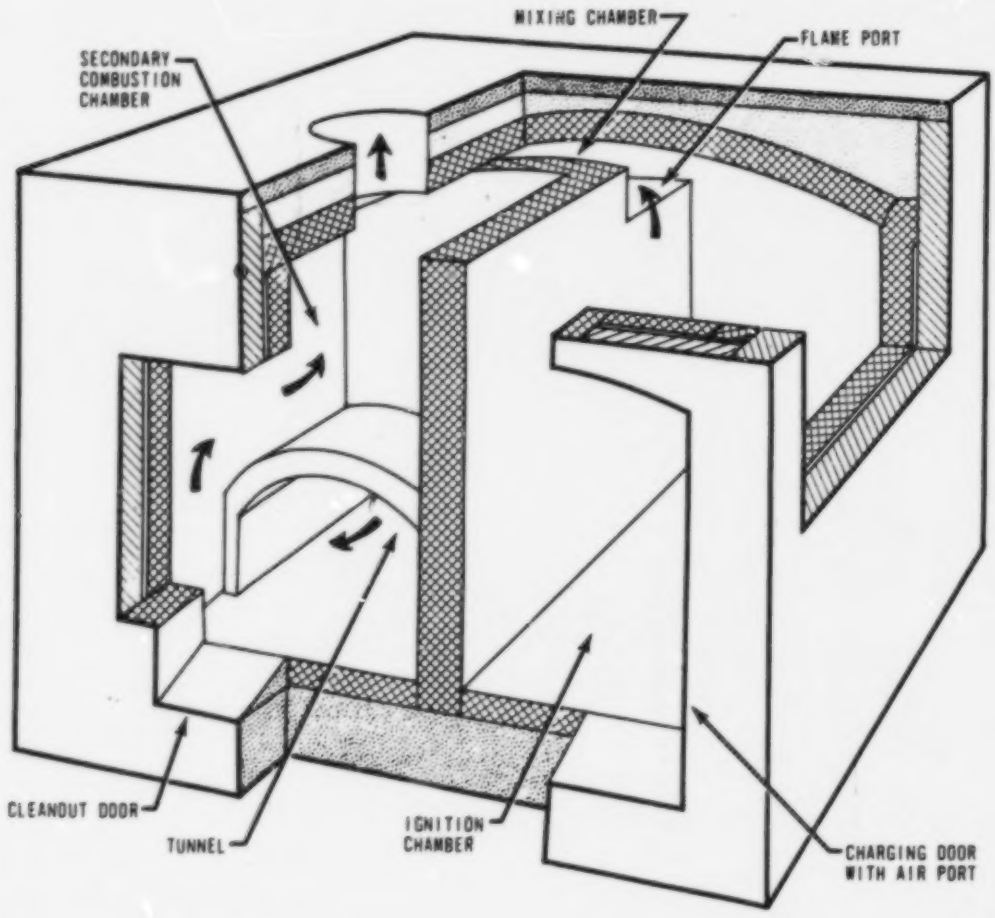


Figure 348. Multiple-chamber retort furnace.

Secondary combustion can actually be initiated in the primary chamber by installing an auxiliary burner with a capacity of about 300,000 Btu per hour through the outside wall of the primary chamber directly opposite the flame port. Flames from this burner start secondary combustion of the effluent from the burning pile before this effluent enters the flame port. Thus, residence time in the secondary combustion zone is increased.

Since fly ash is not present in appreciable amounts, the third chamber can either be eliminated or designed to maintain gas velocities equal to or less than those in the mixing chamber. Figure 349 shows a three-chamber retort furnace designed to burn 1,000 pounds of insulation-covered wire per hour.

General Construction

Construction, in general, follows many practices given for multiple-chamber incinerators described in the first part of this chapter. Only those skilled in installing high-temperature refractories should be employed in constructing this specialized equipment.

Refractories

Although primary ignition chambers can be lined with high-duty fire clay firebrick, secondary mixing chambers, curtain wall port tunnels, and afterburners should be lined with superduty firebrick or superduty plastic refractory.

Since flames may extend into them, stacks must be fully lined with insulating brick or castable refractory with a service temperature of at least 2,500°F. Expansion joints must be provided as specified by the refractory manufacturer.

Charge Door

A side swing charge door is installed in contrast to the guillotine-type door found on multiple-chamber incinerators. Mating surfaces of the door and door jambs are grooved or recessed. The door is provided with a positive locking device, such as a cam or wedge lock, to hold the mating surfaces in close contact. High-heat-duty ASTM Class 24 castable refractory is used to line the charge door.

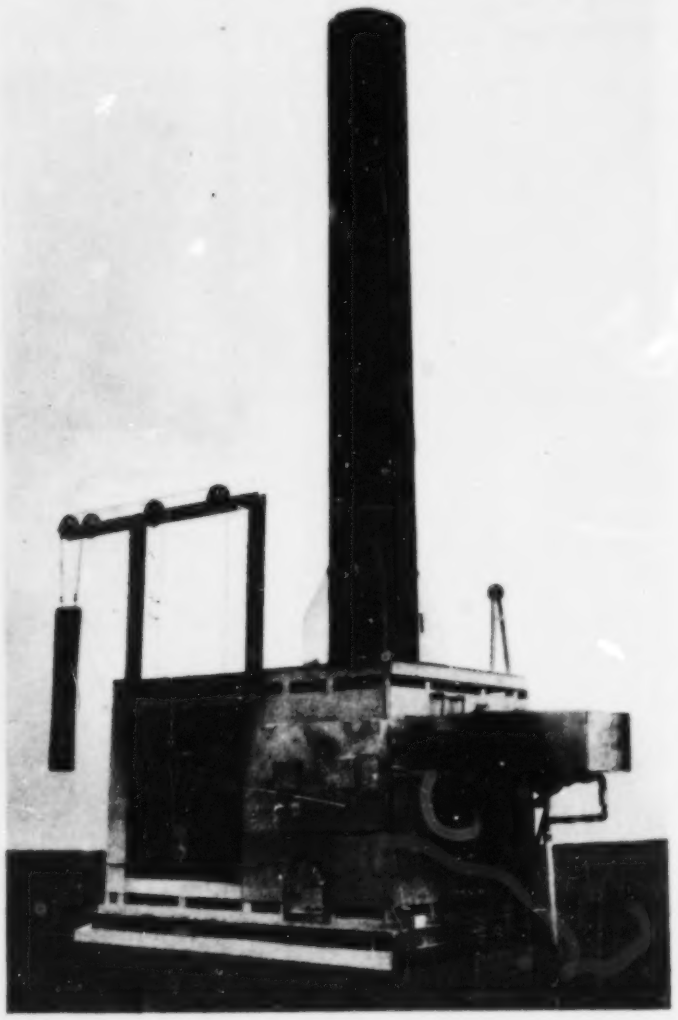


Figure 349. A 1,000-pound-per-hour, multiple-chamber retort furnace (Amana Scrap Metals, Compton, Calif.).

Combustion Air Ports

Air ports in the primary chamber should be constructed of cast iron at least 1/2 inch thick to minimize warpage. Swing-type ports should be used with positive locking devices. Since the exterior surface around the secondary air port is relatively cool, materials of construction used for secondary air ports are not critical. Ten-gage steel plate can be used and snug fits are easily attained.

Gas Burners

To ignite the charge, hand-held natural gas torches or low-capacity, permanently mounted, atmospheric gas burners with flame safety controls may be installed in the primary chamber.

Secondary burners can be of several types--atmospheric, premix, or nozzle mix. They should have flame safety controls and be adjusted to give a long, luminous flame for maximum effectiveness in promoting secondary combustion. Secondary burners should be mounted through the side of the mixing chamber opposite the flame port, and flames from these burners should completely blanket the cross section of the mixing chamber.

Operation

One of the most important factors concerning operation is to restrict the combustion rate in the ignition chamber by tightly closing all primary air ports and sealing the charge door to prevent gaseous overloading of the secondary combustion chamber. If overloading does occur with all openings closed in the ignition chamber, the combustion rate can be further reduced by spraying water onto the burning charge, being extremely careful not to spray directly against the hot refractory walls.

Although primary burners are used simply to ignite the charge, secondary burners are operated throughout the burning period. In fact, the secondary chamber or afterburner should be preheated 10 minutes before a cold lightoff to minimize smoke. Materials must not be removed from the primary chamber before the reclamation process is complete since excessive smoke will be emitted to the atmosphere. Wire is removed from the chamber while hot with only traces of smoke present, and it must be immediately quenched with water to stop the smoke as well as to clean char and residual materials from the reclaimed copper metal.

Secondary air ports should be adjusted to maintain high temperatures in the secondary combustion zone without emissions of black or white smoke from the stack. Black smoke, may indicate a lack of combustion air, which may be eliminated by opening the secondary air ports.

Since the inorganic materials in vinyl-coated wire are emitted to the atmosphere as submicron-size particles even after passing through the secondary combustion zone, the percentage of vinyl-coated wire in a given charge may need to be restricted in order to prevent excessive emissions.

Illustrative Problem

Problem:

Design equipment to process a 250-pound batch of commercial insulated electrical wire containing 25 weight percent combustibles. One batch charge will require 30 min.

Given:

Design calculations apply equally to a single chamber venting to an afterburner or to a multiple-chamber retort-type furnace.

Solution:

1. Primary ignition chamber:

   Assume bulk density of randomly packed wire charge at 4 lb/ft^3. Design ignition chamber 50 percent oversize.

$$(1.50)\left(\frac{250\text{ lb}}{4\text{ lb/ft}^3}\right) = 94.0\text{ ft}^3$$

   Use dimensions of 2.75 ft x 5.25 ft x 3.25 ft high

2. Ignition chamber gas burners:

   Install minimum size gas burners for lightoff.

   Burner capacity = 50 cfh

3. Primary air ports:

   Assume inlet velocity through port is 900 fpm at 0.052 in. WC. Assume 100 percent excess air in ignition chamber and composition of combustibles equivalent to U.S. Grade 6 (P.S. 400) fuel oil. From Table D6, Appendix D, 354.4 scf of air is required for 1 pound of combustibles.

$$\left(\frac{250\text{ lb wire}}{30\text{ min}}\right)\left(\frac{0.25\text{ lb combustibles}}{\text{lb wire}}\right)\left(\frac{354.4\text{ scf}}{\text{lb}}\right) =$$

   737 scfm

   Port area:

$$\left(\frac{737\text{ cfm}}{900\text{ fpm}}\right)\left(\frac{144\text{ in.}^2}{\text{ft}^2}\right) = 118\text{ in.}^2$$

4. Port or duct connecting single chamber to an afterburner (equivalent to a flame port in a multiple-chamber incinerator):

   Design for 30 fps at 1,300°F. Assume 100 percent excess air in ignition chamber. From Table D6, Appendix D, there are 363.3 scf of products from combustion of 1 pound of combustibles.

$$\left(\frac{250\text{ lb wire}}{30\text{ min}}\right)\left(\frac{0.25\text{ lb combustibles}}{\text{lb wire}}\right)\left(\frac{60\text{ min}}{\text{hr}}\right)\left(\frac{363.3\text{ scf}}{\text{lb}}\right)$$

   = 45,300 scfh

   or 755 scfm

   or 12.6 scfs

$$\text{Area} = \left(\frac{12.6\text{ scfs}}{30\text{ fps}}\right)\left(\frac{1,760°\text{R}}{520°\text{R}}\right)\left(\frac{144\text{ in.}^2}{\text{ft}^2}\right)$$

$$= 204\text{ in.}^2$$

5. Secondary air port size:

   Design for 100 percent theoretical air through secondary air ports. Inlet velocity is 900 fpm or 0.051 in. WC. From Table D6, Appendix D, 177.2 scf of air is required per pound of combustibles.

$$\left(\frac{250\text{ lb wire}}{30\text{ min}}\right)\left(\frac{0.25\text{ lb combustibles}}{\text{lb wire}}\right)\left(\frac{177.2\text{ scf}}{\text{lb}}\right) =$$

   368 scfm

$$\text{Port area} = \left(\frac{368\text{ scfm}}{900\text{ fpm}}\right)\left(\frac{144\text{ in.}^2}{\text{ft}^2}\right) = 59\text{ in.}^2$$

6. Equilibrium temperature between products of combustion from ignition chamber at 1,300°F and secondary dilution air at 60°F:

   Weight of secondary dilution air:

$$\left(\frac{250\text{ lb wire}}{30\text{ min}}\right)\left(\frac{0.25\text{ lb combustibles}}{\text{lb wire}}\right)\left(\frac{13.51\text{ lb}}{\text{lb}}\right) =$$

   28.1 lb/min

   Weight of products of combustion from ignition chamber:

$$\left(\frac{250\text{ lb wire}}{30\text{ min}}\right)\left(\frac{0.25\text{ lb combustibles}}{\text{lb wire}}\right)\left(\frac{27.96\text{ lb}}{\text{lb}}\right) =$$

   58.2 lb/min

$$(W_a)(C_{pa})[T_2 - T_a] = W_c(C_{pc})[T_1 - T_2]$$

where

W_a = weight of secondary dilution air, lb/min

C_{pa} = specific heat of air, Btu/lb-°F

T_2 = final gas temperature, °F

T_1 = initial gas temperature, °F

T_a = inlet air temperature, °F

W_c = weight of products of combustion, lb/min

C_{pc} = specific heat of products of combustion, Btu/lb-°F

(28.1 lb/min)(0.26 Btu/lb-°F)(T_2 - 60°F) =

(58.2 lb/min)(0.26 Btu/lb-°F)(1,300°F - T_2)

T_2 = 870°F

7. Secondary burner (afterburner) capacity:

Design secondary burner to raise temperature of products of combustion from ignition chamber and secondary air from 870° to 1,600°F. Assumed specific heat of products of combustion is 0.26 Btu/lb-°F.

$$Q = W_c C_p [T_2 - T_1]$$

where

Q = heat required, Btu/min

W_c = weight of products of combustion from ignition chamber and dilution air, lb/min

C_p = specific heat of products of combustion from ignition chamber and dilution air, Btu/lb-°F

T_2 = final temperature

T_1 = initial temperature

Q = (28.1 lb/min + 58.2 lb/min)(0.26 Btu/lb-°F)

(1,600°F - 870°F)

Q = 16,400 Btu/min or 985,000 Btu/hr

Design secondary burners for 20 percent excess air. From Table D7, Appendix D, the calorific value of 1 scf of natural gas at 1,600°F is 552.9 Btu.

Burner capacity = $\frac{985,000 \text{ Btu/hr}}{552.9 \text{ Btu/scf}}$ = 1,775 cfh

$\frac{\text{Gross secondary heat}}{\text{lb combustibles}} = \frac{(1,775 \text{ scfh})(1,100 \text{ Btu/scf})}{125 \text{ lb/hr}}$

= 15,600 Btu/lb

8. Mixing chamber (afterburner) cross-sectional area:

This area is also equivalent to the cross section of the curtain wall port tunnel of a multiple-chamber unit. Design for 30 fps at 1,600°F and secondary burners for 20 percent excess air. Total volume through mixing chamber:

Products of combustion from ignition chamber	=	45,300 scfh
Secondary gas burners (1,775 cfh)(13.53 cf/cf)	=	24,000 scfh
Secondary air $(368 \text{ scfm})\left(\frac{60 \text{ min}}{\text{hr}}\right)$	=	22,100 scfh
		91,400 scfh
	or	1,520 scfm
	or	25.4 scfs

Cross-section area = $\left(\frac{25.4 \text{ scfs}}{30 \text{ fps}}\right)\left(\frac{2,060°R}{520°R}\right)\left(\frac{144 \text{ in.}^2}{\text{ft}^2}\right)$

= 483 in.^2

9. Total length of secondary combustion chamber (afterburner):

Assume cross-section area of curtain wall port or tunnel is equal to cross section of mixing chamber. Design for a residence time of 0.50 second.

Length of secondary zone = (30 fps)(0.50 sec)

= 15 ft

10. Dilution air port at base of stack:

Design dilution air port to reduce temperature of gases from mixing chamber from 1,600° to 1,200°F. Specific heat of products of combustion and dilution air is 0.26 Btu/lb-°F. From Table D7, Appendix D, there is 0.999 lb products of combustion of 1 scf natural gas with 20 percent excess air.

Products of combustion from ignition chamber	= 58.2 lb/min
Secondary air through port	= 28.1 lb/min
Secondary burner $(1,775 \text{ scfh})(0.999 \text{ lb/scf})\left(\frac{\text{hr}}{60 \text{ min}}\right)$	= 29.6 lb/min
	115.9 lb/min

Total gases:

$W_a C_{pa} [T_2 - T_a] = W_c (C_{pc}) [T_1 - T_2]$

(See calculation No. 7.)

W_a (0.26 Btu/hr-°F)(1,200°F - 60°F) =

(115.9 lb/min)(0.26 Btu/lb-°F)(1,400°F - 1,200°F)

$$1,140\ W_a = 23,200$$

$$W_a = 20.4 \text{ lb/min}$$

Volume of dilution air:

$$\left(\frac{20.4 \text{ lb}}{\text{min}}\right)\left(\frac{379 \text{ scf/lb mole}}{29 \text{ lb/lb mole}}\right) = 267 \text{ scfm}$$

or 4.45 scfs

Assume velocity through dilution air ports is 1,255 fpm or 0.10 in. WC velocity pressure.

$$\text{Port area} = \left(\frac{267 \text{ scfm}}{1,255 \text{ fpm}}\right)\left(\frac{144 \text{ in.}^2}{\text{ft}^2}\right) = 30.6 \text{ in.}^2$$

11. Stack cross-sectional area:

Design for a velocity of 30 fps at 1,200°F.

Total volume of flow:

Gases from mixing chamber =	25.5 scfs
Dilution air at base of stack =	4.4 scfs
	29.9 scfs

Stack cross-sectional area:

$$\text{Area} = (29.9 \text{ scfs})\left(\frac{1,660°\text{R}}{520°\text{R}}\right)\left(\frac{1}{30 \text{ fps}}\right) = 3.18 \text{ ft}^2$$

Select a 24-in.-ID stack

12. Stack height above grade:

Design for a static pressure of 0.20 in. WC at base of stack.

(a) Theoretical draft of a 10-foot section at 1,200°F:

$$D_t = 0.52\ PH\left(\frac{1}{T} - \frac{1}{T_1}\right)^*$$

where

D_t = theoretical draft, in. WC

P = absolute atmospheric pressure, lb/in.^{2}

H = stack height, ft

T = temperature of stack gases, °R

T_1 = temperature of air, °F

$$D_t = (0.52)(14.7)(10)\left(\frac{1}{520} - \frac{1}{1,660}\right) = 0.101 \text{ in. WC}$$

(b) Stack friction for 10-foot section:

$$F = \frac{0.008\ H(V)^2}{D_t\ T}\dagger$$

where

F = friction, in. WC

H = stack height, ft

V = velocity, fps

D = stack diameter, ft

T = absolute stack temperature, °F

$$F = \frac{0.008\ (10)(30)^2}{(2.0)(1,660)} = 0.022 \text{ in. WC}$$

(c) Net effective draft for 10-foot section:

Net draft = a - b = 0.101 - 0.022

= 0.079 in. WC

(d) Stack height, H, above grade:

$$H = \frac{0.20 \text{ in. WC}}{0.079 \text{ in. WC/10 ft}} = 25.4 \text{ ft}$$

*Kent, 1936.

†Griswold, 1946.

CHAPTER 9

COMBUSTION EQUIPMENT

GASEOUS AND LIQUID FUELS

ROBERT T. WALSH, Senior Air Pollution Engineer*

GAS AND OIL BURNERS

ROBERT T. WALSH, Senior Air Pollution Engineer*

BOILERS, HEATERS, AND STEAM GENERATORS

ROBERT T. WALSH, Senior Air Pollution Engineer*

*Now with New York-New Jersey Air Pollution Abatement Activity, National Center for Air Pollution Control, Public Health Service, U.S. Department of Health, Education, and Welfare, Raritan Depot, Metuchen, New Jersey.

CHAPTER 9

COMBUSTION EQUIPMENT

GASEOUS AND LIQUID FUELS

INTRODUCTION

For centuries, combustible materials containing carbon and hydrogen have furnished man with his most versatile source of heat and convertible energy. Recent years have seen him, to a large degree, weaned from the conventional solid fuels--coal, wood, peat, and lignite--in favor of more convenient gaseous and liquid hydrocarbons. Although nuclear power and sunlight will probably become increasingly prominent, hydrocarbons will surely continue to provide a significant portion of our domestic heat and power supply and our vehicle fuels.

The burning of gaseous and liquid fuels is so commonplace that it enters directly into a vast number of air-polluting processes. Most boilers, heaters, ovens, and driers are heated by the combustion of hydrocarbon fuels. Many other processes use steam, hot water, or electrical energy generated from the burning of hydrocarbons.

Whenever hydrocarbon fuels are burned, gaseous oxidation products are formed and, in almost every case, vented to the atmosphere. Optimum combustion of "clean" fuels, for example, natural gas and lightweight oils, results in gases containing essentially water vapor, carbon dioxide, nitrogen, and oxygen--all normal constituents of the atmosphere--as well as some oxides of nitrogen, which are air contaminants. The burning of any fuel under less than optimum conditions produces some quantities of carbon, ash, and unburned and partially burned hydrocarbons. In addition, many fuels contain sulfur and metallic compounds that are, even in the oxidized state, air pollutants.

The fuel picture is changing. Coal, a principal solid fuel in some areas, but not in Los Angeles, has less acceptance than it once enjoyed, because of inherent drawbacks in material handling and combustion, as well as to its tendency to create greater quantities of air pollution. In many instances where coal is employed on a large scale, it is pulverized to facilitate handling and burning. Moreover, treating coal to lower its ash and sulfur contents has become commonplace. The trend is away from high-sulfur, high-ash coals and fuel oils and toward "cleaner" gaseous and liquid fuels. In all fairness it must be reported that coal producers are working vigorously to regain their markets by new techniques, such as pipelining coal slurry, to eliminate certain present disadvantages.

Gaseous Fuels

Most of the fuel gas consumed in the United States is a naturally occurring mixture of low-molecular-weight hydrocarbons, of which methane and ethane predominate. Some natural gases from the well contain hydrogen sulfide and other gaseous sulfur compounds. Natural gas as marketed is, however, extremely pure, so much so that sulfur compounds are usually added to distribution lines (about 0.15 grain, calculated as sulfur, per 100 scf) to impart a detectable odor to the fuel. Because available natural gas supplies often contain small quantities of carbon dioxide and nitrogen and a varying ratio of methane to ethane and higher hydrocarbons, gross heating values range from 900 to 1,200 Btu per scf in different localities. Analyses of some natural gases are presented in Tables 138 and 139.

Table 138. COMBUSTION DATA SUMMARY FOR A TEXAS NATURAL GAS

Analysis	
Component	% by volume
CO_2	0
N_2	5.15
O_2	0
CH_4	81.11
C_2H_6	9.665
C_3H_8	3.505
$L\text{-}C_4H_{10}$	0.19
$N\text{-}C_4H_{10}$	0.24
C_5H_{12}	0.09
C_6H_{14} and higher	0.05
	100.00

Gross heating value, 1,100 Btu/scf	
Combustion air requirement, scf/scf	
Theoretical	10.36
20% excess	12.43
100% excess	20.72

Products of combustion, per 1 scf				
Component	At theoretical air		At 20% excess air	
CO_2	1.134 scf	0.132 lb	1.134 scf	0.132 lb
H_2O	2.083 scf	0.099 lb	2.083 scf	0.099 lb
N_2	8.236 scf	0.609 lb	9.821 scf	0.726 lb
O_2	-	-	0.435 scf	0.037 lb
Total	11.453 scf	0.840 lb	13.473 scf	0.994 lb

Table 139. COMBUSTION CHARACTERISTICS OF GASEOUS FUELS

Material	Density, lb/ft³ at 60°F	Analysis, % by volume									Inert	Heating value, Btu/ft³ at 60°F		Theoretical air requirement, ft³ dry air/ft³ fuel	CO_2 in dry products of combustion at theoretical air, % by volume
		H_2	CH_4	C_2H_4	C_2H_6	C_3H_6	C_3H_8	C_4H_8	C_4H_{10}	C_5H_{12}		Gross	Net		
Pure hydrocarbons[a]															
Hydrogen	0.0053	100										325	275	2.38	0
Methane	0.0422		100									1,010	910	9.57	11.6
Ethane	0.0792				100							1,770	1,619	16.75	13.1
Ethylene	0.0746			100								1,614	1,513	14.29	15
Propane	0.1162						100					2,520	2,319	23.90	13.7
Propylene	0.1110					100						2,336	2,186	21.44	15
Butane	0.1530								100			3,265	3,014	31.10	14
Natural gases															
Los Angeles, Calif.	0.0460		81.1		9.7		3.5		0.4	0.1	5.2	1,100	990	10.36	11.9
Birmingham, Ala.[b]	0.0460		90		5						5	1,002	904	9.44	11.8
Kansas City, Mo.[b]	0.0453		84.1		6.7						9.2	974	879	9.17	11.8
Pittsburgh, Pa.[b]	0.0467		83.4		15.8						0.8	1,129	1,021	10.62	12
Refinery process gases[a]															
Cracked, dry	0.0572	-	64.5	----	16	1.9	6.7	1.3	2.9	0.6		1,316	1,200	12.34	11.5
Coking, dry	0.0628	9.5	44.6	3.6	24.3	1.5	14	----	2.5	---		1,463	1,340	14	--
Reforming, dry	0.0795	4.9	27.5	7.4	27.6	3	22.4	----	7.2	---		1,745	1,592	16.90	--
Cracked, dry	0.0755	3.8	40.2	3.3	21.2	1.1	23.8	----	6.6	---		1,617	1,475	15.20	--
Fluid cat., dry	0.0776	5.5	31.7	7	9.7	15.1	24.7	----	0.4	---	6.5	1,609	1,470	15.90	--
Thermafor cat., dry	0.0663	19.5	24.6	8.2	9.6	10	20.6	----	----	---	7.5	1,384	1,264	13.70	--
Refinery, dry	0.0740	3.3	36	5.4	18.2	7.5	19.7	----	1.9	---	8	1,540	1,407	15.70	--
Fluid cat., butane-free	0.0815	13.3	16.1	7.9	7.1	36.4	19.2	----	----	---		1,804	1,621		--
Avg cat. reformer	0.0210	80.8	5	----	4.9	----	9.3	----	----			641	569	5.47	7.02
						C_4H_{10}	CO	CO_2	O_2	N_2					
Miscellaneous gases[b]															
Coke oven	0.0306	51.9	32.3	----	----	3.2	5.5	2	0.05	4.9		569	503	5.45	10.8
Blast furnace	0.0782	1	----	----	----	----	27.5	11.5	----	60		92	92	0.68	25.5
Water	0.0536	32.5	4.6	----	----	0.7	28.2	5.5	0.9	27.6		260	239	2.07	14.9
Carbureted water	0.0414	49.6	10.9	----	2.5	6.1	21.9	3.6	0.4	5		536	461	5.05	14

[a]Nelson, 1958.
[b]The North American Manufacturing Co., 1952.

In addition to natural gas, several other gases, some mixtures, some pure compounds, are used as combustion fuels. These range from by-product and manufactured gases to liquefied petroleum gas (LPG). Typical analyses of available gaseous fuels are listed in Table 139. Some by-product gases such as refinery "make gas" contain appreciable percentages of higher molecular weight hydrocarbons so that their heating values are somewhat greater than those of natural gases. Most by-product and manufactured gases contain significant quantities of carbon monoxide and inerts such as nitrogen and carbon dioxide, resulting in heating values ranging from 100 to 600 Btu per scf.

Bottled liquefied petroleum gas consists of one or a mixture of the following: Propane, propylene, butane, and butylene. Because of its ease of liquefaction and relatively high gross heating value--2,520 to 3,265 Btu per scf--the use of LPG has been steadily increasing over the past few decades. It finds its greatest application as natural gas standby fuel, as vehicular fuel, in portable equipment, and for general use in remote areas to which piping less expensive fuels, such as natural gas, is not practical.

Oil Fuels

The term fuel oil applies to a wide range of liquid petroleum products including crude oil, distillates, and residuals. Most products marketed as fuel oils have been refined to some degree to remove impurities and to fix upper and lower limits of gravity, flash point, viscosity, and heating value. The sulfur and ash contents and the viscosity are the major characteristics that affect air contaminant emissions.

Table 140 provides United States Bureau of Standards specifications for fuel oils. These standards often serve as guides in fuel selection rather than as rigid limitations. Suppliers are likely to market fuels that meet the needs of their localities and that are normal products of their particular crude oil stocks and refining processes. These fuels frequently do not fit into any one of the classifications listed in Table 140. Products such as these are commonly sold under a company name such as Diesel Furnace Oil, Low-Sulfur Stove Oil, or Light Crack Residual Oil.

In Table 140, Numbers 1 and 2 are distillate oils, while Numbers 5 and 6 are residuals or "bottoms" from refinery processes. Number 4 oils are likely to be distillates or blends containing appreciable distillate stock. The Bureau of Standards does not list a Number 3 oil.

In general, the distillate oils contain appreciably lesser concentrations of the potential air contaminants--sulfur and ash--than the more viscous residuals do. This can be seen from the recommended specifications in Table 140. It is a result of the fact that most of the sulfur and ash in crude

Table 140. COMMERCIAL STANDARDS FOR FUEL OILS[a] (Commercial Standard CS 12-48)

Grade of fuel oil[b]		Flash point, °F	Pour point, °F	Water and sediment, %	Carbon residue on 10% residuum, %	Ash, %	Gravity, °API	Distillation temperatures, °F			Kinematic viscosity							
											Seconds, Saybolt				Centistokes at			
Number[c]	Description							10% point	90% point	End point	Universal at 100°F		Furol at 122°F		100°F		122°F	
		min	max	max	max	max	min	max	max	max	max	min	max	min	max	min	max	min
1	Distillate oil intended for vaporizing pot-type burners and other burners requiring this grade[d]	100 or legal	0	Trace	0.15	---	35	420	---	625	---	---	---	---	2.2	1.4	---	---
2	Distillate oil for general purpose domestic heating for use in burners not requiring No. 1	100 or legal	50[e]	0.10	0.35	---	26	[f]	675	---	40	---	---	---	(4.3)	---	---	---
4	Oil for burner installations not equipped with preheating facilities	130 or legal	20	0.50	---	0.10	---	---	---	---	125	45	---	---	26.4	(5.8)	---	---
5	Residual-type oil for burner installations equipped with preheating facilities	130 or legal	---	1.00	---	0.10	---	---	---	---	---	150	40	---	---	32.1	(81)	---
6	Oil for use in burners equipped with preheaters permitting a high-viscosity fuel	150 or legal	---	2.00[g]	---	---	---	---	---	---	---	---	300	45	---	92)	(638)	---

[a] Recognizing the necessity for low-sulfur fuel oils used in connection with heat treatment, nonferrous metal, glass, and ceramic furnaces, and other special uses, a sulfur requirement may be specified in accordance with the following table:

Grade of fuel oil	Sulfur max, %
No. 1	0.5
No. 2	1.0
Nos. 4, 5, and 6	No limit

Other sulfur limits may be specified only by mutual agreement between the buyer and seller.

[b] It is the intent of these classifications that failure to meet any requirement of a given grade does not automatically place an oil in the next lower grade unless in fact it meets all requirements of the lower grade.

[c] Grade No. 3 became obsolete with the issuance of the 1948 commercial standard for fuel oils.

[d] No. 1 oil shall be tested for corrosion in accordance with ASTM Designation D130-30 for 3 hours at 122°F. The exposed copper strip shall show no gray or black deposit.

[e] Lower or higher pour points may be specified whenever required by conditions of storage or use. These specifications shall not, however, require a pour point lower than 0°F under any conditions.

[f] The 10% point may be specified at 440°F maximum for use in other than atomizing burners.

[g] The amount of water by distillation plus the sediment by extraction shall not exceed 2.00%. The amount of sediment by extraction shall not exceed 0.50. A deduction in quantity shall be made for all water and sediment in excess of 1.0%.

oil is tied up in long-chain, high-boiling-point organic compounds, which tend to concentrate in residuals from refinery processes. Moreover, most effective sulfur-removing processes are adaptable only to low-viscosity distillate oils.

Table 141 provides combustion data for a U.S. Grade 6 residual fuel oil. Residual fuel oils are markedly less expensive than distillate oils but require more elaborate burner equipment for proper combustion. "Heavy crack" residual fuels are normally burned, therefore, only in large combustion sources. Most small operators, particularly those who burn natural gas on a curtailable basis, prefer to use cleaner, more trouble-free distillate oils as stand-by.

THE AIR POLLUTION PROBLEM

Air contaminants generated from fuel burning fall into three categories: (1) Carbon and the unburned and partially oxidized organic materials that result from incomplete combustion, (2) sulfur oxides and ash directly attributable to fuel composition, and (3) oxides of nitrogen formed at firebox temperatures from oxygen and nitrogen of the air. Incomplete combustion products can usually be held to tolerable minimums with proper operation of modern burner equipment. Sulfur and ash emissions are governed by the fuel makeup. Nitrogen oxide concentrations are primarily functions of firebox design and temperature.

Black Smoke

When hydrocarbon fuels are burned in a deficiency of oxygen, some carbon particles can be found in the products of combustion. With poor fuel atomization, inadequate mixing, or marked oxygen shortage, the concentration of carbon increases to the point where a visible blackness is imparted to exit gases. Black smoke, when it occurs, is usually connected with the burning of viscous, heavy-crack residual oils and of solid fuels. Creating black smoke by burning gaseous fuels is difficult, though not impossible. Other products of incomplete combustion, such as carbon monoxide, usually accompany black smoke emissions. The degree of blackness is historically significant, since the Ringelmann Chart was developed for this type of smoke. Heavy, carbonaceous accumulations in exhaust stacks, commonly termed soot, are attributable to the same cause as black smoke, namely, poor combustion.

White Smoke

Visible emissions ranging from grey through brown to white can also be created in the combustion of hydrocarbon fuels, particularly liq-

Table 141. COMBUSTION DATA SUMMARY FOR A NUMBER SIX FUEL OIL

Analysis	
Component	% by weight
Carbon	88.3
Hydrogen	9.5
Sulfur	1.6
Water	0.05
Ash	0.10

Gross heating value
152,000 Btu/gal
18,000 Btu/lb

Combustion air requirement (dry)

	scf/lb	lb/lb
Theoretical	176.3	13.4
10% excess	193.9	14.8
20% excess	211.6	16.1
100% excess	352.6	26.9

Products of combustion, per lb of fuel oil
Assume air at 40% RH, 60°F

Component	At theoretical air		At 20% excess air	
CO_2	27.9 scf	3.24 lb	427.9 scf	3.24 lb
H_2O	19.3	0.92	19.5	0.93
SO_2	0.2	0.03	0.2	0.03
N_2	139.3	10.30	167.5	12.38
O_2	---	---	7.4	0.64
Total	186.7	14.49	222.5	17.22

uid fuels. White or opaque smoke, that is, non-black smoke, is the result of finely divided particulates--usually liquid particulates--in the gas stream. These visible pollutants are most often caused by vaporization of hydrocarbons in the firebox, sometimes accompanied by cracking, and subsequent condensation of droplets at 300° to 500°F stack temperatures. White smoke is frequently attributed to excessive combustion air (cold fire) or loss of flame (gassing). Visible contaminants can also exist where combustion is optimum and the concentration of oxidizable materials is at a minimum. This situation is apparently limited to large power plant boilers where there is measurable sulfur trioxide in exhaust gases.

Particulate Emissions

Combustion gases can contain particulate matter in the form of unburned carbon and hydrocarbon as well as inorganic ash. With the proper use of adequate burner equipment, oxidizable particulates, both solids and liquids, can usually be kept well below typical emission standards, for example, Rule 53b of the Los Angeles County Air Pollution Control District allows 0.3 grain of particulate matter per scf of exhaust gases calculated on a 12 percent carbon dioxide basis. Where unburned particulate concentrations approach allowed limits the Ringelmann number or opacity of the exhaust gases is usually high and may exceed legal standards for visible contaminants. The operator of combustion equipment malfunctioning in this way can almost always correct the combustion conditions to control these emissions unless the grade of fuel is improper for the combustion equipment or vice versa. Ash collected at large, efficient power plant boilers during oil burning normally contains less than 10 percent carbon and other combustibles.

The quantity of inorganic solid particulates in exhaust gases is entirely dependent upon the characteristics of the fuel. There is no measurable inorganic ash in exhaust gases from the combustion of natural gas or other clean gaseous hydrocarbons, except for that small quantity attributable to the dust usually present to some degree in all air used for combustion. Distillate fuel oils do not contain appreciable amounts of ash. Typical analyses show variations from a trace to about 0.03 percent by weight. In residual oils, however, inorganic ash-forming materials are found in quantities up to 0.1 percent by weight. Most of this material is held in long-chain organo-metallic compounds. The strong oxidation conditions present in most fireboxes convert these materials to metallic oxides, sulfates, and chlorides. As would be expected, the compounds show up as finely divided particulates in exhaust gases. Table 142 provides a spectrographic analysis of the inorganic fuel oil ash collected at a large power plant boiler.

The combined ash and unburned particulates in exhaust gases from gaseous or liquid fuel combustion are not likely to exceed local air pollution control statutes. For instance, the efficient burning of a common heavy residual oil of 0.1 percent ash results in a stack gas concentration of only 0.030 grain per scf at 12 percent carbon dioxide.

Sulfur in Fuels

In liquid hydrocarbon fuels, sulfur occurs in concentrations ranging from a trace to more than 5 percent by weight. Much of this sulfur is present as malodorous sulfides and mercaptans. Natural gas fuels contain very little sulfur as marketed, usually only enough to impart a detectable odor to the gas. Some by-product gases, however, contain appreciable sulfides and mercaptans. Distillate oils may contain as much as 1 percent sulfur, though most distillates have less than 0.3 percent.

There is normally much more sulfur in heavy residual oils than in gaseous fuels and distillate oils.

Most of these oils contain more than 1 percent sulfur by weight. In the Los Angeles area the heavy residual oil commonly burned in power plant boilers averages 1.6 percent sulfur. The only low-sulfur (less than 0.5 percent) residual oils available are those resulting from the refining of low-sulfur crude oils, which are relatively rare.

Table 142. TYPICAL FUEL OIL ASH ANALYSIS

Constituent	Weight %
Iron	22.99
Aluminum	21.90
Vanadium	19.60
Silicon	16.42
Nickel	11.86
Magnesium	1.78
Chromium	1.37
Calcium	1.14
Sodium	1
Cobalt	0.91
Titanium	0.55
Molybdenum	0.23
Lead	0.17
Copper	0.05
Silver	0.03
Total	100

Sulfur Oxides

Most of the sulfur present in fuels is converted to sulfur dioxide on combustion. A typical residual fuel oil of 1.6 percent sulfur yields a concentration of 1,000 ppm sulfur dioxide when burned with the theoretical amount of combustion air. As shown in the sample calculations, this is equivalent to 832 ppm at 20 percent excess combustion air, a point at which many industrial boilers are operated.

In some combustion processes, a small portion of the sulfur--usually no more than 5 percent of the total--is converted to sulfur trioxide, the anhydride of sulfuric acid. Sulfur trioxide is highly reactive and extremely hygroscopic as compared with sulfur dioxide. It is considered a chief cause of the visible plume created by burning high-sulfur fuel oils in large power plant boilers. Besides obscuring visibility, these contaminants can result in acid damage to vegetation and property in downwind areas. The factors governing firebox formation of sulfur trioxide are not fully understood, but it is recognized to occur principally in large combustion installations operated at high firebox temperatures.

Oxides of Nitrogen

In every combustion process the high temperatures at the burner result in the fixation of some oxides of nitrogen. These compounds are found in stack gases mainly as nitric oxide (NO) with lesser amounts of nitrogen dioxide (NO_2) and only traces of other oxides. Since NO continues to oxidize to NO_2 in the air at ordinary temperatures, there is no way to predict with accuracy the amounts of each separately in vented gases at a given time. The total amount of NO + NO_2 in a sample is determined and referred to as "oxides of nitrogen" or NO_x (Los Angeles County Air Pollution Control District, 1960a).

AIR POLLUTION CONTROL METHODS

An operator can take only two options to reduce air contaminant emissions from a combustion source, namely, remove the sulfur compounds and ash from his combustion gases or switch to a cleaner and usually more expensive fuel. Only limited progress has been made in removing air pollutants from combustion products. These methods are discussed later in this chapter in the section, "Boilers, Heaters, and Steam Generators," inasmuch as they are employed only at large combustion sources.

Prohibitions Against Sulfur Emissions

Two types of regulations have been used to limit the concentration of sulfur contaminants at combustion sources and thus outlaw the burning of certain fuels. One sets a ceiling on the fuel's sulfur content while the other fixes a maximum allowable flue gas concentration. Both types of prohibitions have been enacted in Los Angeles County. Rule 53a limits the concentration of sulfur compounds in exhaust gases from any combustion process to 0.2 percent by volume calculafed as sulfur dioxide. Rules 62 and 62.1 prohibit the burning of gaseous fuels containing more than 50 grains of sulfur compounds per 100 cubic feet, calculated as hydrogen sulfide, and liquid fuels containing more than 0.5 percent sulfur by weight. Rules 62 and 62.1 are considerably more stringent than Rule 53a, limiting sulfur concentrations to roughly one-eighth of that allowed by Rule 53a. Until practical stack control methods are developed, either type of regulation will be effective in prohibiting the burning of high-sulfur fuels, on the assumption that the chosen concentrations are comparable.

Supplementary provisions are sometimes used wherein allowable stack sulfur emissions are based upon ground level concentrations, usually measured as sulfur dioxide. The regulations of the San Francisco Bay Area Air Pollution Control District, for instance, set an effluent limit of 0.2

percent as sulfur dioxide but allow heavier discharges of sulfur compounds, provided ground level concentrations do not exceed specified limits. The allowed concentrations are on a sliding time basis ranging from 3 minutes at 1.5 ppm to 8 hours at 0.3 ppm, sulfur compounds being measured as sulfur dioxide. Obviously, statutes such as these allow heavier emissions where dispersion conditions are favorable and where the source is isolated from similar sulfur-emitting plants.

Removal of Sulfur and Ash From Fuels

To whatever degree is economically feasible, hydrocarbon fuels are treated to remove sulfur compounds as well as inorganic ash. The practical sulfur removal methods are essentially restricted to scrubbing or liquid-liquid extraction, sometimes accompanied by catalytic decomposition. Natural gas is commonly scrubbed at the natural gas plant before its introduction into transmission pipe lines. Higher molecular weight hydrocarbon gases and distillate oils are treated at the refinery before they are marketed.

There is at present no economical method of removing sulfur from heavy residual oils. As was previously mentioned, most of the sulfur in these viscous oils is tied up in large molecules. To remove the undesirable sulfur, one must remove it from the molecule, as with hydrocracking or thermal cracking processes, and thereby create hydrocarbons of considerably lower molecular weights. Both these processes add appreciably to fuel costs and are now used to yield products such as gasoline and distillate oils, which command markedly higher prices than residuals. The ash tends to concentrate in the residuals.

Apparently, on the basis of present technological trends, yields of residual oils from refineries will be steadily reduced in coming years. New processes being developed and perfected are aimed primarily at greater yields of gasoline and diesel and aircraft fuels. Much more work is being done on the development of these processes than on methods of removing sulfur from highly cracked residual oils.

Figure 350 shows production trends for residual and distillate oils over the period 1943 through 1962. Obviously, residual yields dropped off sharply while distillate production increased in inverse proportion. The yield curve for residual oil is expected to continue to decline as existing refinery equipment is replaced. Much of the oil listed as distillate in Figure 350 is used as motor fuel, while almost all the residual oil is burned in boilers and heaters. Over the 20-year period from 1943 to 1962, refinery crude oil input increased approximately twofold. Residual production decreased, therefore, in terms both of volume and yield in that interval. This situation has been offset somewhat by the increased importation of residual oil.

Illustrative Problem

The following example illustrates calculations used in determining sulfur oxides and ash content in flue gases formed by burning a heavy residual fuel.

Example 34

Given:

A heavy residual fuel is to be burned in a combustion process with 20 percent excess air. The oil analyses, % by weight, is as follows:

Carbon	88.3
Hydrogen	9.5
Sulfur	1.6
Water	0.05
Ash	0.10

Problem:

Determine the combustion air requirement and the concentration of sulfur oxides in flue gases while assuming 3 percent of the sulfur is converted to sulfur trioxide. Determine the ash concentration in flue gases at 12 percent carbon dioxide while assuming complete combustion. Use as a basis 1 pound of fuel oil.

Solution:

1. Theoretical combustion air requirement:

Carbon $C + O_2 \longrightarrow CO_2$

$(0.883 \text{ lb})\left(\frac{32}{12}\right) = 2.35 \text{ lb } O_2 = 132.5 \text{ scf of air}$

Hydrogen $H_2 + 1/2\ O_2 \longrightarrow H_2O$

$(0.095 \text{ lb})\left(\frac{16}{2}\right) = 0.76 \text{ lb } O_2 = 42.9 \text{ scf of air}$

Sulfur $S + O_2 \longrightarrow SO_2$

$(0.016)\left(\frac{32}{32}\right) = 0.016 \text{ lb } O_2 = 0.9 \text{ scf of air}$

Total

176.3 scf of dry air/lb oil

177.6 scf air at 40% RH, 60°F per lb oil

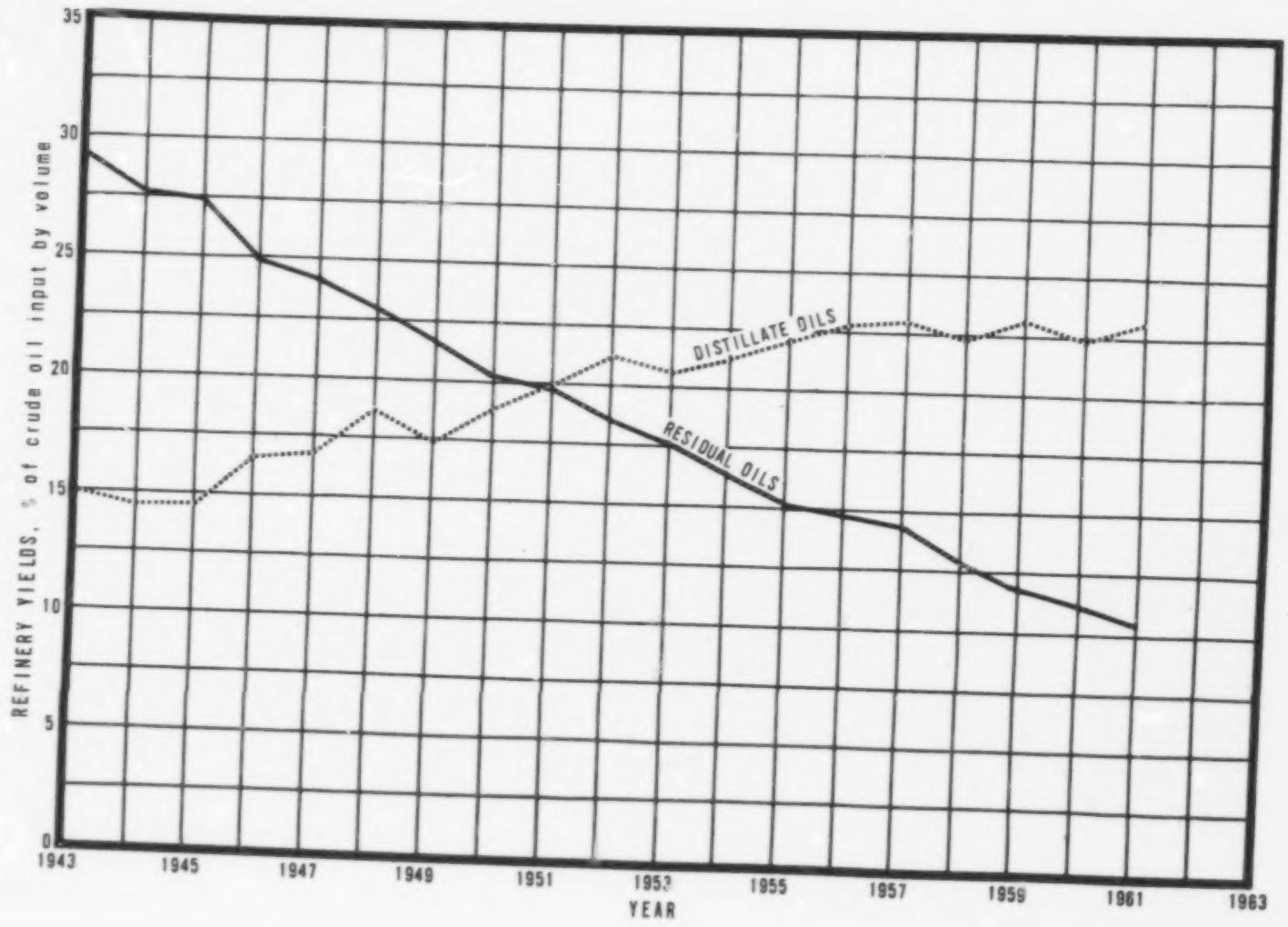


Figure 350. Production trends, U.S. refineries, 1943-1962.

2. Air requirement at 20% excess air:

(176.3)(1.20) = 212 scf dry air/lb oil

(177.6)(1.20) = 213 scf moist air/lb oil

3. Products of combustion (assume complete combustion and neglect SO_3):

Carbon dioxide

$$(0.883 \text{ lb})\left(\frac{44}{12}\right)\left(\frac{379 \text{ scf}}{44 \text{ lb/mol}}\right) = 27.9 \text{ scf}$$

Water from combustion

$$(0.095 \text{ lb})\left(\frac{18}{2}\right)\left(\frac{379}{18}\right) = 18.0 \text{ scf}$$

Water in fuel:

$$0.0005 \text{ lb}\left(\frac{379}{18}\right) = 0.011 \text{ scf}$$

Nitrogen

(212 scf)(0.79) = 167.5 scf

Water in air, 40% RH, 60°F

(0.0072 scf/scf air)(213 scf) = 1.5 scf

Sulfur oxides as sulfur dioxide

$$0.016\left(\frac{64}{32}\right)\left(\frac{379}{64}\right) = 0.2 \text{ scf}$$

Oxygen

(176.3 scf)(1.20 - 1.00)(0.21) = 7.4 scf

Total 222.5 scf/lb oil

4. Sulfur dioxide concentration:

$$(0.016)\left(\frac{379}{32}\right)\left(\frac{1}{222.5}\right)(10^6)(0.97) = 827 \text{ ppm}$$

5. Sulfur trioxide concentration:

$$(0.016)\left(\frac{379}{32}\right)\left(\frac{1}{222.5}\right)(10^6)(0.03) = 26 \text{ ppm}$$

6. Inorganic ash concentration:

$$(0.001 \text{ lb})(7,000 \text{ gr/lb})\left(\frac{1}{222.5}\right) = 0.0314 \text{ gr/scf}$$

GAS AND OIL BURNERS

INTRODUCTION

A burner is essentially a triggering mechanism used to ignite and oxidize hydrocarbon fuels. In general, burners are designed and operated to push the oxidation reactions as close as possible to completion with the maximum production of carbon dioxide and water, leaving a minimum of unburned and partially oxidized compounds in exhaust gases. Burner efficiency can be measured by the water and carbon dioxide contents of combustion gases or, conversely, by the concentrations of carbon monoxide, carbon, aldehydes, and other oxidizable compounds. Insofar as hydrocarbon-derived pollutants are concerned, optimum burner operation goes hand in hand with minimum air pollution.

The purpose of this part of the chapter is to present general burner principles with emphasis on major design and operation variables that affect air pollution. There are so many variations in burner design that discussing each separately would not be practical. Specific operating instructions for any given burner should be obtained from the manufacturer or agent.

Burners and the combustion equipment in which they are located are commonly thought of as sources of air pollution. Burners, however, are also used frequently as air pollution control equipment. Their most common control application is in vapor incineration, but many are used for purposes such as refuse incinerator auxiliaries and as tempering heaters with baghouses, precipitators, and centrifugal collectors. Almost all burners used in air pollution control devices are designed to handle gaseous fuels exclusively.

A burner consists primarily of a means of metering the two reactants, oxygen and fuel, and a means of mixing the reactants before and concurrently with ignition. Many burners also include flame safety devices and auxiliaries to condition the temperature and viscosity of the fuel, as well as fans and pumps to move or pressurize air or fuel. The simplest burners are employed with gaseous combustion fuels while the most complex units are used with heavy oils and with solid fuels.

Draft Requirements

In all combustion equipment, some energy is required to push or pull the combustion air, fuel, or products of combustion through the burner and also through the heat exchange portion of the combustion equipment. With small gas-fired appliances, the line gas pressure together with the bouyancy of warm oxidation products are sufficient to provide the necessary draft. With larger equipment, either extended natural-draft stacks or blowers must be used. Blowers may be positioned ahead of or behind the firebox. When located ahead of the firebox, a blower is sometimes constructed as an integral part of the burner and is driven by a motor common to a fuel pump or atomizing device. Forced-draft burners provide greater flexibility and can be used in situations where the firebox itself is under pressure.

Gas Burners

Owing principally to the low viscosity of gaseous fuels, gas burners are considerably simpler than those used with liquid and solid fuels. Gaser can be transmitted and mixed with combustion air much more easily than other fuels can. This is not to say that all gas burners are necessarily uncomplicated mechanisms. Many are equipped with elaborate combustion air auxiliaries and flame control features. For a specific installation, however, a gas burner is almost always less complicated than its liquid or solid fuel-burning counterpart designed for the same application.

In most gas burners, only a portion of the air requirement--termed primary combustion air--is mixed with fuel before ignition. These burners constitute the large majority of equipment in use today, ranging from small appliances to large power plant gas burners. Two other types in reasonably wide use do not fall into this category--totally aerated burners and nonprimary aerated burners.

With totally aerated burners, all combustion air is mixed with fuel before ignition. These units are employed at installations such as metallurgical furnaces, where operation within narrow oxygen concentration limits or even in reducing atmospheres is desirable.

In nonprimary aerated burners, no combustion air is mixed with fuel ahead of the burner port. The gaseous fuel is merely allowed to jet through an orifice in such a pattern or manner as to provide adequate mixing with oxygen. Most of these units

employ narrow slotted ports, giving the flame a thin fan shape. In other nonprimary aerated burners, a circular orifice is employed, and the jetted fuel is allowed to impinge on a target surface in such a manner as to provide turbulence and mixing. Many nonprimary aerated burners are of multiport design, employing a number of slots or orifices in order to provide maximum interface surface between fuel and combustion air.

Partially Aerated Burners

The venturi-shaped burner in Figure 351 can be used to illustrate the basic operation of partially aerated atmospheric gas burners. Gaseous fuel is introduced through the control valve into the burner head and allowed to flow through the fixed orifice into the throat. The jetted gas stream induces combustion air to flow through the primary airport and creates enough turbulence to mix fuel and air between the orifice and the burner tip. The quantity of primary air induced is governed by the airport setting, the specific gravity of the gas, and the gas pressure. Ignition starts at the burner tip where additional air--termed secondary combustion air--contacts the mixture. Combustion is completed off the burner tip as additional secondary air reacts with the burning mixture.

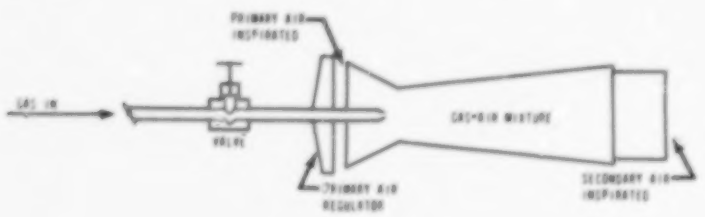


Figure 351. Typical atmospheric gas burner.

yellow tip curve results in a smoky flame with possible flashback. Natural gases are relatively slow burning and are not likely to flash back unless conditions are severe.

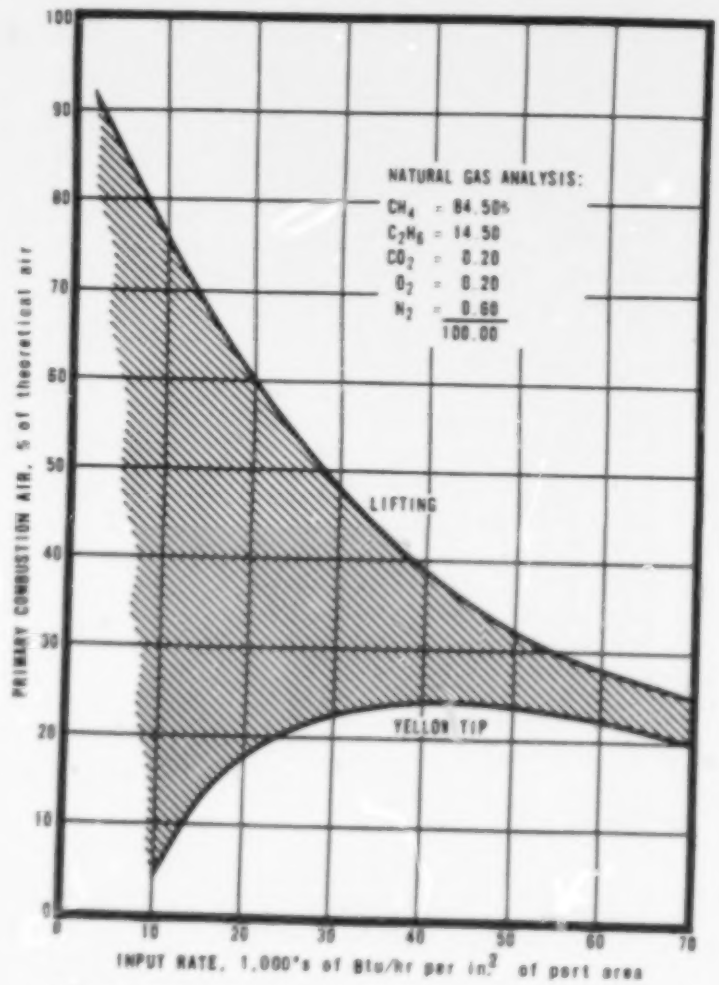


Figure 352. Flame stability limits burning a natural gas in an atmospheric burner (American Gas Association Laboratories, 1940).

For a given fuel, the combustion efficiency and the stability, shape, and luminosity of the flame are dependent upon the primary and secondary air rates and the degree of turbulence. A high primary air rate produces a short, blue flame, while a low primary air rate results in a long, luminous flame. If primary air is reduced too greatly, the flame becomes smoky with yellow tips, and flashback may occur out the primary combustion airport. If the primary air rate is increased too much, the flame becomes unstable and lifts from the burner port. These limits are plotted in Figure 352 for an 1,100 Btu per cubic foot natural gas. The cross-hatched area between the two curves represents the stable range of burner operation for a typical partially aerated burner. Operation above the lift curve results in the flame's lifting from the burner, while operation below the

The effect of primary air at the same gas input is illustrated in Figure 353 for the same natural gas described in Figure 352. At the maximum primary air rate shown, 66.8 percent of the theoretical combustion requirement, the inner blue cone of the flame is sharply defined while the outer luminous cone is almost indistinguishable at the tip. At the lowest primary air rate, 49.1 percent, the flame becomes extremely luminous, the inner blue cone blending into the luminous outer cone.

The burner characteristics of different fuel gases are dependent to a large degree upon speeds of flame propagation. Gases such as hydrogen, carbon monoxide, ethylene, benzene, and propylene, with high ignition velocities, are prone to flashback through the burner at low primary air rates.

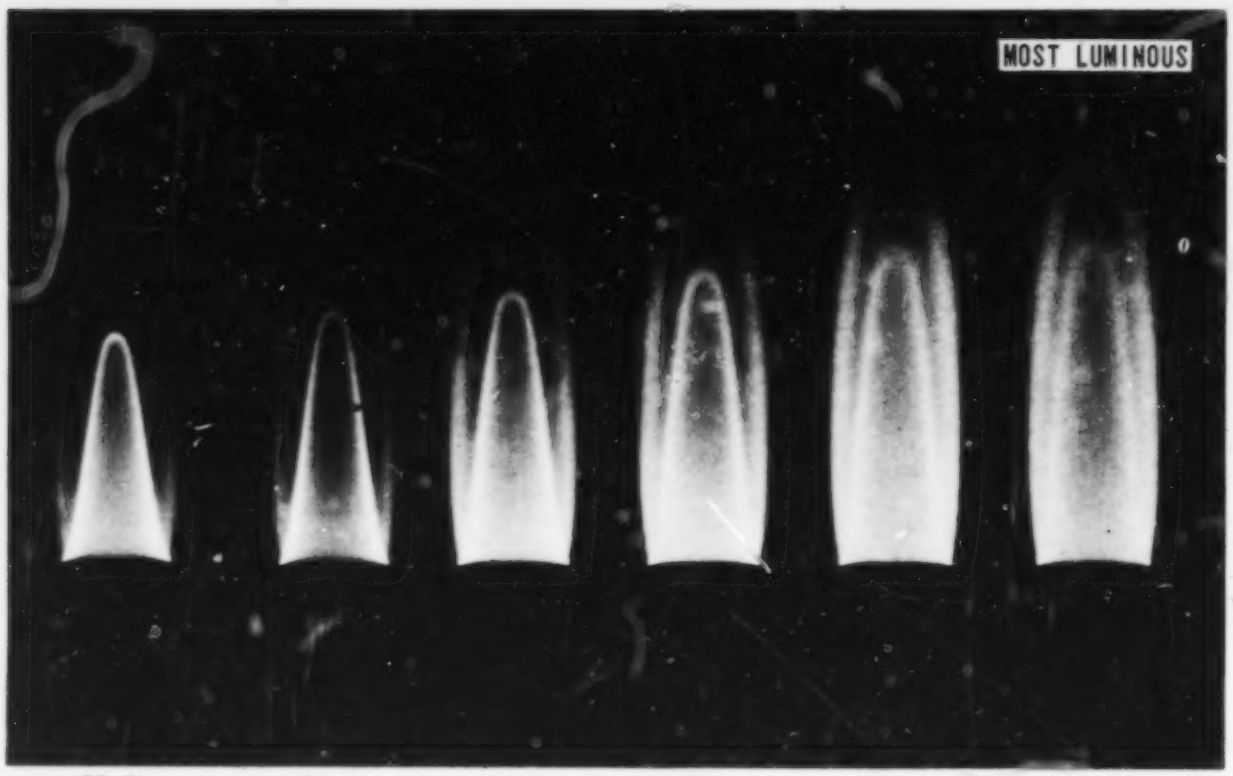


Figure 353. Natural gas flames with varying primary air (American Gas Association Laboratories, 1940).

Nevertheless, the latter fast-burning gases do not tend to blow off or lift from the burner tip as readily as the slower burning fuels, methane, ethane, and butane. Gases with high ignition velocities are, therefore, normally operated at somewhat higher primary air rates than natural gas and liquefied petroleum gas are. This can be seen by comparing the stability range of the fast-burning manufactured gas of Figure 354 with that of the natural gas of Figure 352. The lift curve for the manufactured gas is considerably higher than for natural gas. For example, at 70 percent primary air and 30,000 Btu per hour per square inch of port area, the manufactured gas flame is stable, while that of natural gas is unstable. The yellow tip curve for this gas is also higher. Its marked propensity to burn back out the air port is shown by the flashback limit curve.

Other factors, such as port size and shape, also influence burner operation. The reader should consult a burner handbook and publications of the American Gas Association for detailed discussions of the subject.

Multiple-Port Gas Burners

Burners with multiple orifices are widely used in boilers, heaters, and vapor incinerators. The individual ports are usually of partial-aeration or nonprimary-aeration design. Over a given cross-section, a multiple-port burner provides better distribution of flame and heat than a single-port unit does. For this reason, multiple-port burners have an inherent advantage in vapor incineration.

Forced-Draft Gas Burners

The availability of a combustion air blower provides greater flexibility and often better combustion than an atmospheric gas burner affords. The simplest forced-draft units consist merely of low-pressure fans with gaseous fuel orifices located in the discharges. In some cases, the fuel is introduced ahead of the blower and allowed to mix in the fan housing. One of the more complex designs is the low-pressure premix unit, shown in Figure 355. Here, a blower is used to force combustion air through a venturi at pressures up

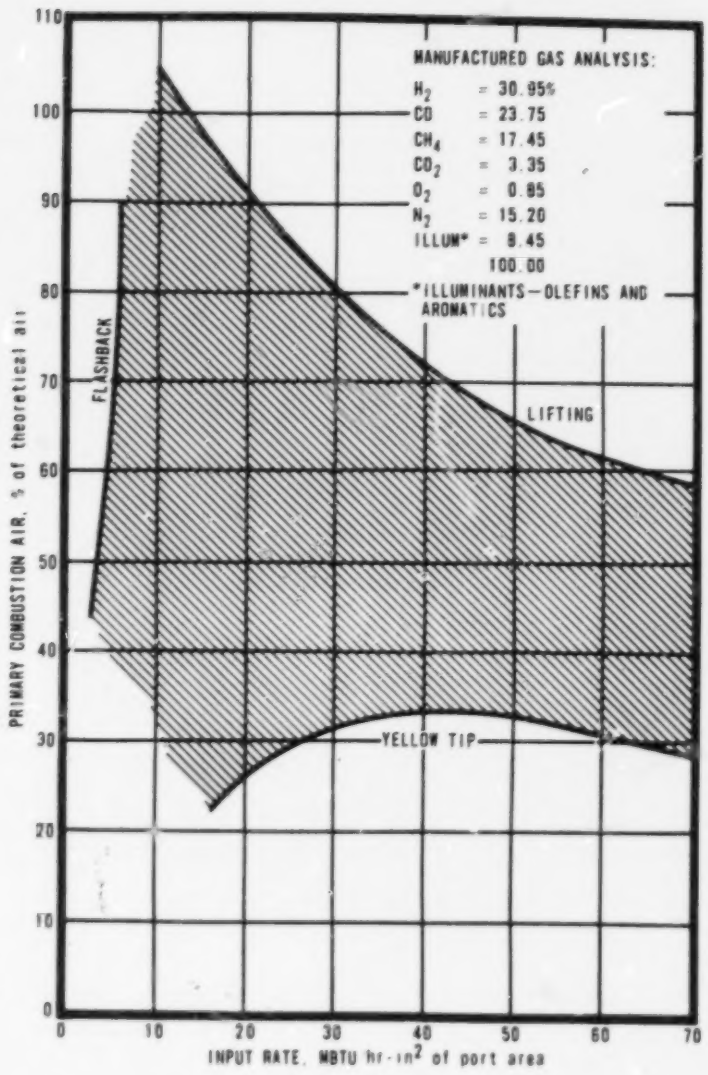


Figure 354. Flame stability limits burning a manufactured gas in an atmospheric burner (American Gas Association Laboratories, 1940).

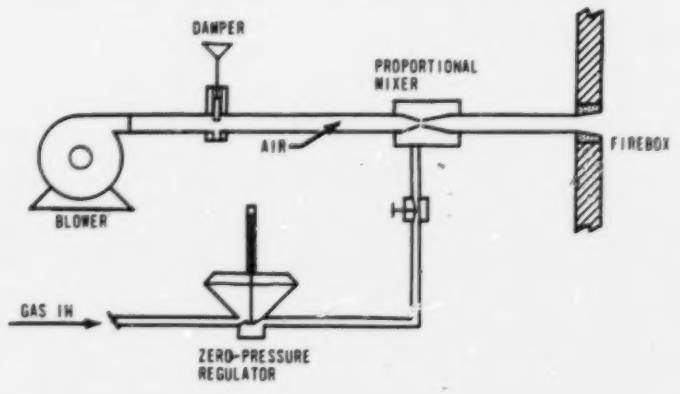


Figure 355. A multiple-port burner (nonprimary aerated) installed in a vapor incinerator.

to 3 psig. Gaseous fuel is drawn into the system at the throat of the venturi and mixes in fixed proportion with combustion air ahead of the burner nozzle. With an arrangement such as this, the shape, makeup, and luminosity of the flame can be precisely controlled. Moreover, the flame has appreciable velocity. These burners are employed in metallurgical processes where precise atmospheric control is desired, in some vapor incinerators, and in crematories and pathological-waste incinerators, where a strong flame must be directed on animal tissue.

Gas Flow Rates

Gaseous fuel is commonly introduced through one or more fixed orifices at the burner. These orifices constitute the principal pressure drop in the gas-piping system and govern the flow of fuel to the burner. Flow through an orifice is proportional to the square root of gas pressure so that minor upstream pressure fluctuations do not have a great effect on flow rate. The nomographs of Figures 356 and 357 provide flow rates for 0.65 specific gravity (referred to air) natural gas through standard orifices at various gas pressures.

Oil Burners

Inasmuch as liquid fuels must be vaporized before combustion can take place, an oil burner must accomplish an additional function not required of a gas burner. Light oils can be vaporized from a static vessel or wick. This principle is used with items such as kerosene lamps and blow torches but is not practical for most burners. In almost all industrial applications, the fuel is first atomized then allowed to vaporize on absorbing heat from the flame. The efficiency of an oil burner depends largely upon atomization and fuel-air mixing.

There are four basic types of oil burners, differing principally in the methods of atomization: Low-pressure air-atomizing; high-pressure steam- or air-atomizing; high-pressure oil-atomizing; and centrifugal or rotary cup burners. A fifth type, the mechanical atomizing burner, employs both high-pressure oil and centrifugal action.

With low-pressure, air-atomizing burners, such as that shown in Figure 358, a major portion of the combustion air requirement is supplied near the oil orifice at 1/2 to 5 psig. This air abrades and atomizes the jetted oil stream in an area of high turbulence. Secondary combustion air is admitted around the periphery of the mixture. In comparison with other types of oil burners, these units provide a greater volume of air in close proximity to the atomized oil--from 10 to 60 percent of the theoretical combustion requirement. For this reason, the flame is reasonably short.

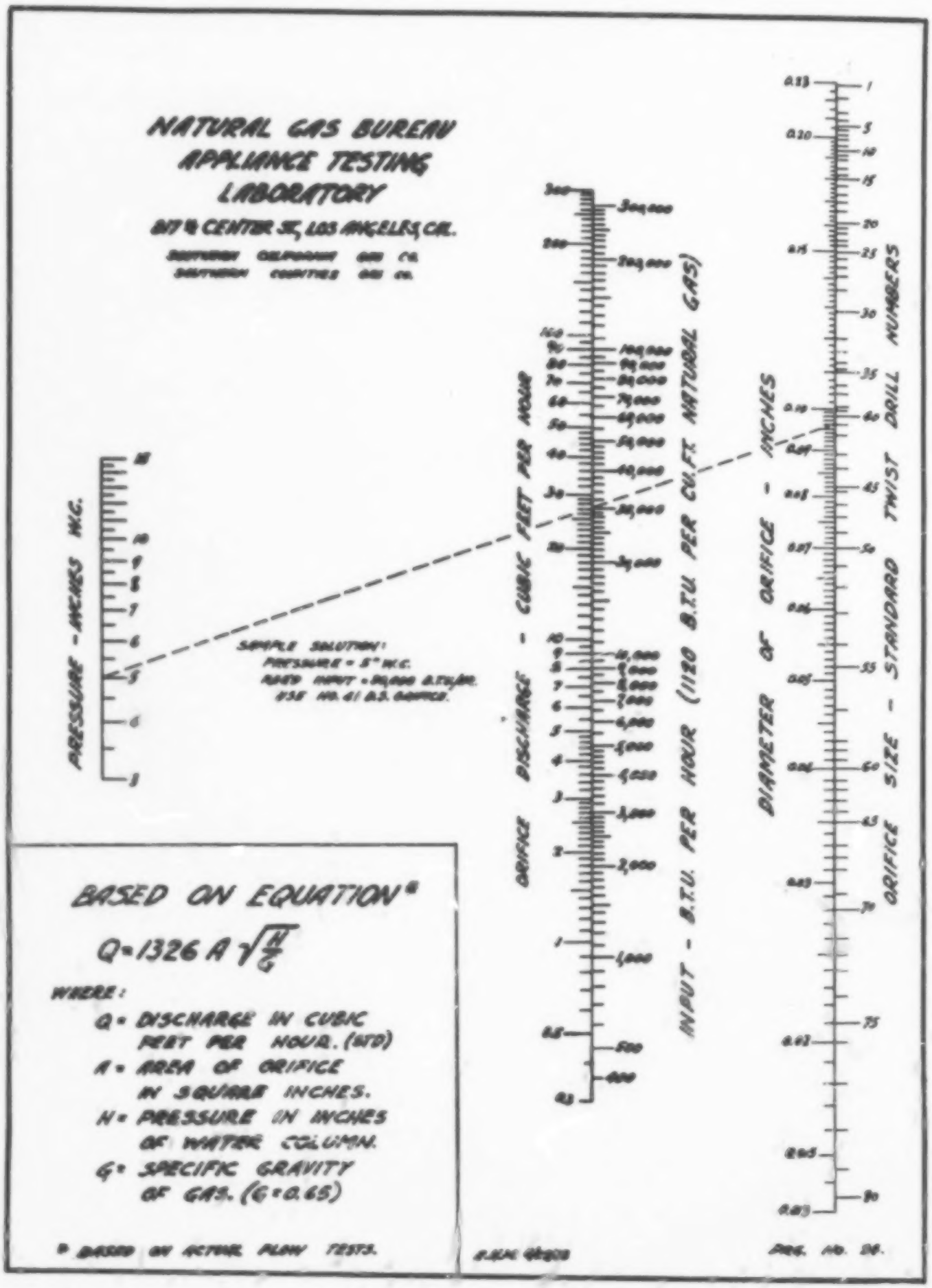

NATURAL GAS BUREAU
APPLIANCE TESTING
LABORATORY
817 N CENTER ST, LOS ANGELES, CAL.
SOUTHERN CALIFORNIA GAS CO.
SOUTHERN COUNTIES GAS CO.
PRESSURE - INCHES W.G.
SAMPLE SOLUTION:
PRESSURE = 5" W.C.
ORIFICE DISCHARGE - CUBIC FEET PER HOUR
INPUT - B.T.U. PER HOUR (1120 B.T.U. PER CU.FT. NATURAL GAS)
DIAMETER OF ORIFICE - INCHES
ORIFICE SIZE - STANDARD TWIST DRILL NUMBERS
BASED ON EQUATION*
Q = 1326 A √(N/G)
WHERE:
Q = DISCHARGE IN CUBIC FEET PER HOUR. (60°)
A = AREA OF ORIFICE IN SQUARE INCHES.
N = PRESSURE IN INCHES OF WATER COLUMN.
G = SPECIFIC GRAVITY OF GAS. (G = 0.65)
* BASED ON ACTUAL FLOW TESTS.
PROJ. NO. 24.

Figure 356. Natural gas flow through standard orifices (Southern California Gas Co.).

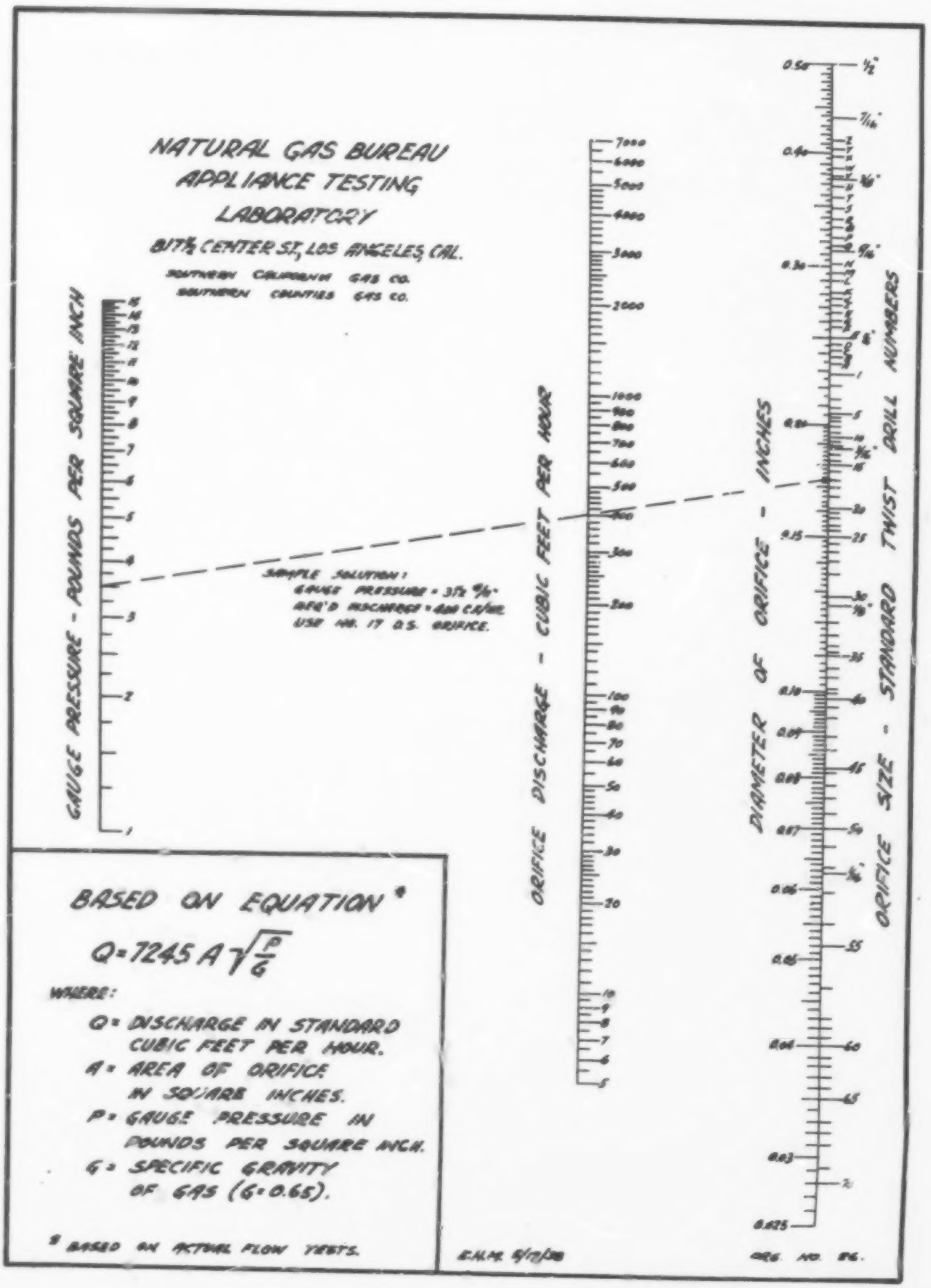

NATURAL GAS BUREAU
APPLIANCE TESTING
LABORATORY
817½ CENTER ST, LOS ANGELES, CAL.
SOUTHERN CALIFORNIA GAS CO.
SOUTHERN COUNTIES GAS CO.
GAUGE PRESSURE - POUNDS PER SQUARE INCH
ORIFICE DISCHARGE - CUBIC FEET PER HOUR
DIAMETER OF ORIFICE - INCHES
ORIFICE SIZE - STANDARD TWIST DRILL NUMBERS
SAMPLE SOLUTION:
GAUGE PRESSURE = 3½ #/in²
REQ'D DISCHARGE = 600 C.F./HR.
USE NO. 17 D.S. ORIFICE.
BASED ON EQUATION *
$Q = 7245\,A\sqrt{\frac{P}{G}}$
WHERE:
Q = DISCHARGE IN STANDARD CUBIC FEET PER HOUR.
A = AREA OF ORIFICE IN SQUARE INCHES.
P = GAUGE PRESSURE IN POUNDS PER SQUARE INCH.
G = SPECIFIC GRAVITY OF GAS (G = 0.65).
* BASED ON ACTUAL FLOW TESTS.
E.H.H. 6/17/38
ORIF. NO. SIZE

Figure 357. Natural gas flow through standard orifices (Southern California Gas Co.).

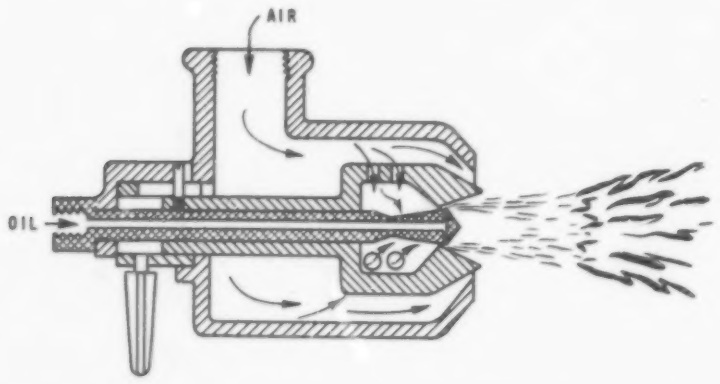


Figure 358. Low-pressure, air-atomizing oil burner (Hauck Manufacturing Co., 1953).

With the high-pressure, steam- or air-atomizing burners of Figure 359, an auxiliary fluid--steam or air--is used to break up the fuel oil stream at the burner tip. The auxiliary fluid, moving at high velocity, atomizes the slower moving oil stream as the mixture passes into the burner tile. The atomizing fluid is provided at pressures ranging from 30 to 150 psig. The volume of atomizing air, when used, is normally much smaller than that encountered with low-pressure, air-atomizing burners. Compressed-air consumption ranges from 30 to 200 cubic feet of free air per gallon of oil, that is, from 2 to 14 percent of the theoretical combustion requirement. These burners are reasonably inexpensive and are likely to be employed where oil is burned only infrequently, as on a standby basis. Steam-atomizing burners perform satisfactorily at viscosities of 150 to 200 Sabolt Seconds Universal (hereafter referred to as SSU). Air-atomizing burners require lower viscosities, usually 80 to 100 SSU.

Oil pressure atomizing burners depend upon high fuel pressure (75 to 150 psig) to cause the oil to break up into small droplets upon passing through an orifice. The fixed orifices of these units are considerably smaller than those used with other types of oil burners. An inherent disadvantage is that the burner atomizes properly only over a fairly narrow pressure range.

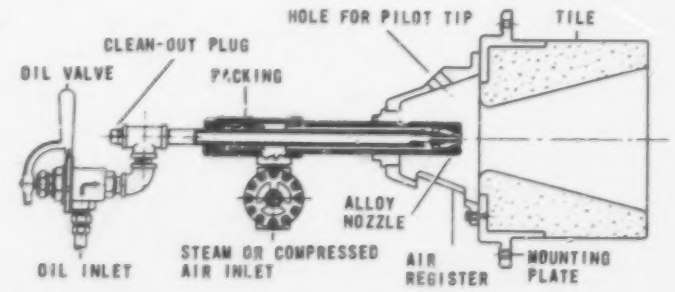


Figure 359. High-pressure, steam- or air-atomizing oil burner (North American Manufacturing Co., 1952).

Mechanical atomizing burners are the most common oil burners found at large power plant steam generators. In the wide-range mechanical atomizing assembly shown in Figure 360, the fuel oil is given a strong whirling action before it is released through the orifice. Proper atomization is dependent upon centrifugal velocities, which in turn require high pressures, that is, 100 to 200 psig. The wide-range unit of Figure 361 overcomes a principal disadvantage of this type burner, namely a narrow turndown ratio. In the burner, some of the whirling oil flows through the orifice while excess oil is drawn off through the central oil return line.

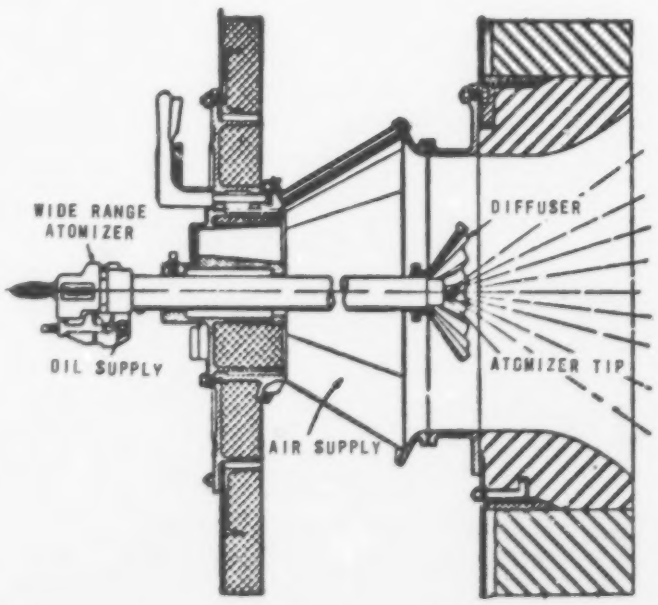


Figure 360. Wide-range mechanical atomizing burner (de Lorenzi, 1947).

Rotary cup burners, such as that shown in Figure 362, provide atomization by centrifugally throwing the fuel from a rotating cup or plate. Oil is distributed on the cup in a thin film. As with oil pressure atomizing burners, no air is mixed with the oil before atomization. Combustion air is admitted through an annular port around the rotary cup. These burners are usually constructed with integral forced-draft blowers. A common motor often drives the oil pump, rotating cup, and blower. Rotary cup burners can be used to burn oils of widely varying viscosity, ranging from distillates to residuals of greater than 300 SSU.

Viscosity and Oil Preheaters

The key to optimum oil burner operation is careful control of fuel viscosity. A given burner func-

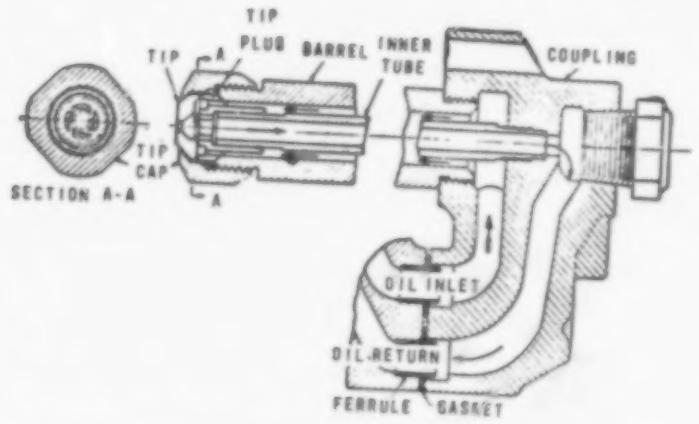


Figure 361. A wide-range mechanical-atomizing assembly with central oil return line (de Lorenzi, 1947).

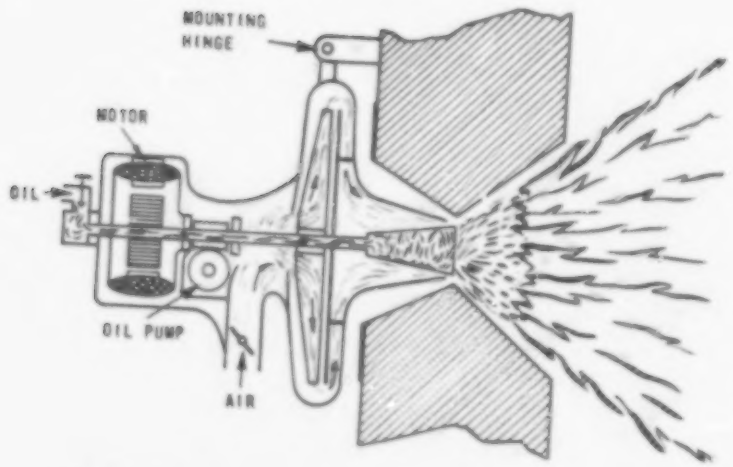


Figure 362. Rotary cup oil burner (Hauck Manufacturing Co., 1953).

tions properly only if the viscosity at the burner orifice is held between fairly narrow limits. If the viscosity is too high, effective atomization does not take place. If the viscosity is too low, oil flow through the orifice is too great, upsetting the balance between combustion air and fuel. There are several viscosity measurement scales.

At viscosities of less than 100 SSU, fuel oils can be burned efficiently in almost any burner. Most burners are designed for optimum performance at 150 SSU or lower. All distillate oils and some blends are of less than 100 SSU at 60°F, as shown in Figure 363. Where fuel oil viscosity at ambient temperature is not compatible with the burner, preheaters are used. With the chart provided in Figure 363, fuel oil viscosities can be estimated at different temperatures. The sloped lines represent fuels with average viscosity-temperature relationships. When the viscosity at a given temperature is known, viscosities at other temperatures can be predicted by extending lines of parallel slope. The chart also allows conversion from different viscosity scales.

Oil preheaters may be mounted directly on the burner, at the supply tank, or just about any place in between. Preheater selection is dependent to a large degree upon the fuel itself. Most heavy residual oil must be warm to allow pumping. A preheater for such oil is likely, therefore, to be located at or near the supply tank. With lower viscosity oils, preheaters are often located at the burner, preheat temperatures are lower, and the heaters are normally smaller and less complicated.

Oil preheaters are operated with either electricity or steam. Electrical heaters allow a greater degree of flexibility. They can be used at times when the combustion equipment is cold and no steam is available. Where only steam preheat is used, an auxiliary source of steam independent of the combustion equipment on which the burner is located should be available. If an oil burner is ignited from a cold start, and the oil is not preheated to its normal temperature, igniting the burner is often difficult or impossible. Excessive air contaminants can be expected from this practice.

THE AIR POLLUTION PROBLEM

The burning of combustion fuels can produce sulfur oxides, inorganic ash, oxides of nitrogen, carbon, and unburned and partially oxidized hydrocarbons. Most of these contaminants, notably sulfur oxides and inorganic ash, are attributable directly to the fuel and are independent of equipment design or operation. The principal air contaminants affected by burner design and operation are oxidizable materials--carbon, carbon monoxide, aldehydes, organic acids, and unburned hydrocarbons. To a lesser degree, burner design can also affect oxides of nitrogen, but these emissions are dependent largely upon the design of the furnace and other combustion equipment.

Smoke and Unburned Contaminants

Modern burner equipment has been perfected to the point where all common fuels can be burned without causing excessive discharges of oxidizable materials in exhaust gases. If the proper combination of burner and fuel has been selected, and if the burner is operated properly, no visible emissions should be caused by oxidizable air contaminants, and the concentrations of items such as aldehydes and carbon monoxide should be negligible. Nevertheless, smoke and oxidizable materials are often found in burner exhaust products.

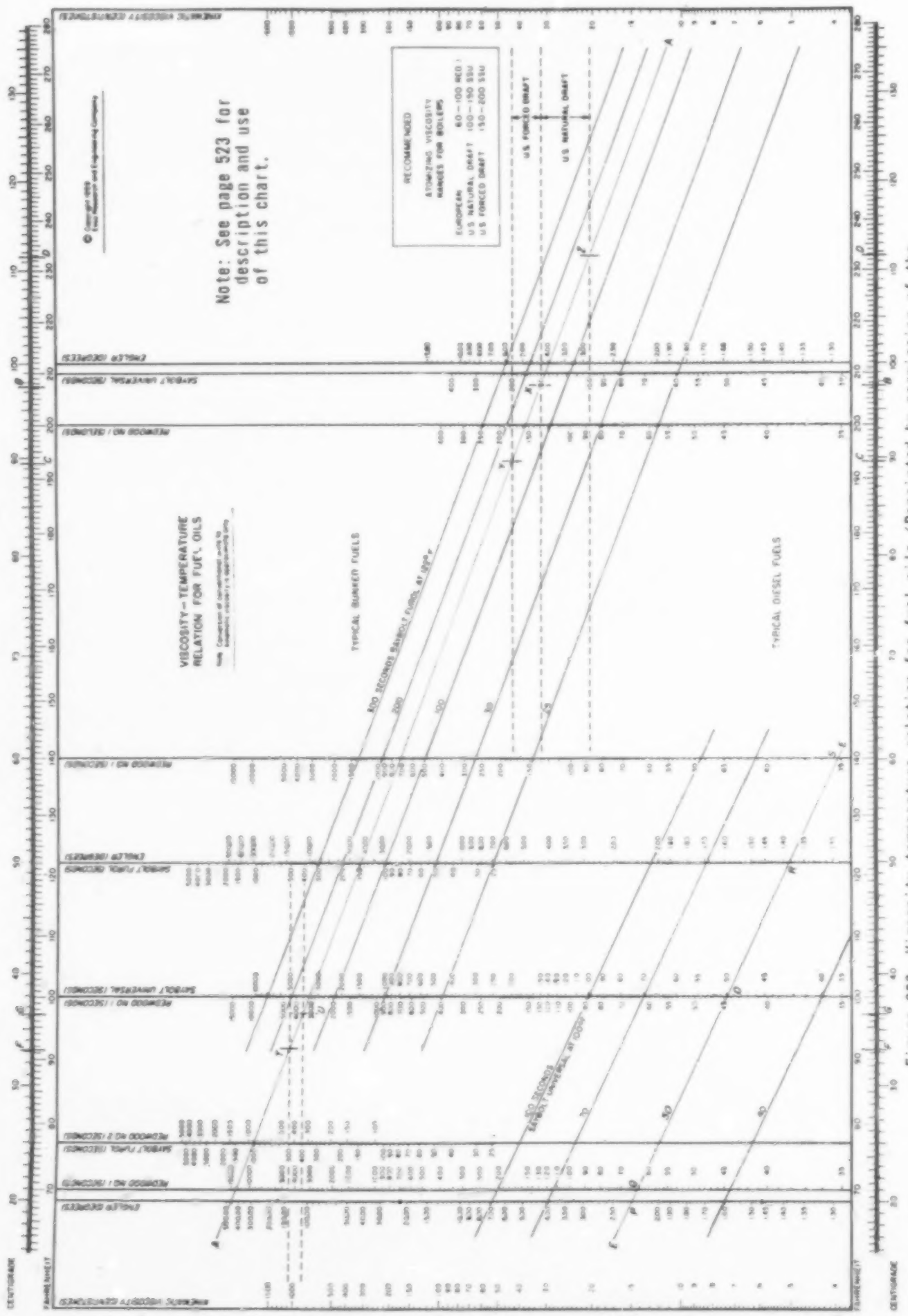

VISCOSITY – TEMPERATURE RELATION FOR FUEL OILS
TYPICAL BUNKER FUELS
TYPICAL DIESEL FUELS
Note: See page 523 for description and use of this chart.
RECOMMENDED ATOMIZING VISCOSITY RANGES FOR BOILERS
EUROPEAN 60–100 REDI
U.S. NATURAL DRAFT 100–150 SSU
U.S. FORCED DRAFT 150–200 SSU
U.S. FORCED DRAFT
U.S. NATURAL DRAFT
CENTIGRADE
FAHRENHEIT

Figure 363. Viscosity-temperature relation for fuel oils (Reprinted by permission of the copyright owner, Esso Research and Engineering Co., Linden, N.J.).

VISCOSITY TEMPERATURE RELATION FOR FUELS

Description of the Chart

The horizontal scales at the top and bottom of the chart are identical and represent temperature, both in degrees Fahrenheit and Centigrade.

The vertical scales represent viscosity in terms of the several methods of measurement now in common use. These scales appear opposite the temperatures at which each customarily is standardized for measuring liquid fuels; namely—

Viscosity Measurement	*Temperature*
Saybolt Universal	at 100°F. 210°F.
Saybolt Furol	at 77°F. 122°F.
Engler Degrees	at 20°C. 50°C. 100°C.
Redwood No. 1	at 70°F. 100°F. 140°F. [illegible]9°F.
Redwood No. 2 (Admiralty)	a[illegible]7°F.
Kinematic	at both edges

Conversion of viscosity from one unit to another by means of the chart is reasonably accurate for all practical purposes. Caution should be used, however, when using the chart to convert a given viscosity unit to kinematic viscosity at various temperatures. The reason for this lies in the fact that the conversion factors to kinematic vary slightly with temperature and therefore, a single kinematic scale cannot be precise at all temperatures. The approximate values obtained from the chart, however, should be sufficiently accurate for practical purposes, such as finding the proper atomizing temperature or limits of pumpability in this viscosity unit. For a more precise conversion from Redwood, Saybolt or Engler units to kinematic viscosity, reference should be made to the specific conversion factors usually found in technical handbooks covering flow of fluids.

Viscosity, of course, decreases with increase in temperature. The diagonal lines, accordingly, represent the average slopes in viscosity encountered with bunker and diesel fuels, respectively. As the chart is prepared logarithmically, the slopes appear as two groups of straight parallel lines. While these particular slopes will not hold with all oils, they do serve as a good index in the majority of cases, and should therefore prove sufficiently accurate for most practical purposes.

The dotted horizontal lines in the right section of the chart indicate the ranges of viscosity recommended for best atomizing fluidity by American burner manufacturers. In Saybolt Universal measurement, the top line represents 200 seconds; the center line 150 seconds; the bottom line 100 seconds. To obtain proper atomization with most installations, viscosity at the burners should fall within the upper range for forced draft, and within the lower range for natural draft. This rule, however, has certain important exceptions in the case of European burner practice as explained on the chart.

The dotted horizontal lines in the upper left section indicate the maximum range of viscosity which will assure free and efficient pumping. These lines represent, respectively, 400 seconds and 500 seconds Saybolt Furol. When equipped for heavy-duty transfer, in which suction head is not a problem, it is possible to pump without difficulty at the upper limit, or even above in some instances. However, it is preferable not to allow viscosity to exceed the lower limit.

To Find Viscosity at Different Temperatures

Knowing the viscosity of an oil in one scale at one temperature, to determine its viscosity in the same or a different scale at a different temperature the procedure given in the following example is used.

Let us assume a diesel fuel having a known viscosity Redwood No. 1 (at 100°F.) of 44.7 seconds. This viscosity is indicated by point "O".

Through "O" we draw the line E-E parallel to the nearest diagonal. The line E-E intercepts Redwood No. 1 again at "Q" (70°F.) showing 64 seconds, and at "S" (140°F.) showing 35.2 seconds. It also intercepts Engler at "P" (20°C.) showing 2.26 degrees, and at "R" (50°C.) showing 1.382 degrees. In this particular case, the only interception of Saybolt Universal which would fall within the chart is likewise at "O" (100°F.) showing 50 seconds.

In a like manner, viscosity conversions between different scales and standardized temperatures can quickly be found from any other known viscosity.

To Find the Proper Atomizing Temperature

Let us assume that you have a bunker fuel oil having a viscosity of 150 seconds Saybolt Furol (at 122°F.). Through this point draw the parallel "A-A". The same line, of course, would apply if we assumed the same oil, knowing its viscosity only in terms of one of the other scales, such as 3500 seconds Saybolt Universal (at 100°F.).

The line "A-A" intercepts the upper and lower ranges of atomizing viscosity between "Y-X" and "X-Z", respectively. Temperature ranges corresponding to these viscosity ranges are then readily found by laying a straight-edge vertically on the chart and noting the points "C", "B" and "D" on the top and bottom temperature scales. In this case, the temperature for 200 seconds Saybolt Universal viscosity is 193°F; for 150 seconds it is 207.5°F. and for 100 seconds 232.8°F. The atomizing range would be 193-207.5°F. for forced draft or 207.5-232.8°F. for natural draft.

As a general rule, the lower the viscosity, the better the atomization: hence, where difficulty is experienced in obtaining complete combustion, as evidenced by excessive smoke, or by dry soot which sometimes is noticeable even with a clear stack, it may prove advisable to operate in the higher temperature (lower viscosity) range with forced as well as natural draft. Severe cases may require raising the oil temperature to correspond to the point of lowest practicable atomizing viscosity (the interception of the lowest dotted line). However, engineers must be guided by prevailing conditions. No fixed rule will apply in all instances.

To Find the Limit of Pumping Temperature

Let us assume a Grade "C" bunker fuel oil having a known viscosity Saybolt Furol (at 122°F.) of 150 seconds. Through this point we draw the parallel "A-A". The temperatures "F" and "G" corresponding to the points of interception "T" and "U" are found in the same manner as described above.

Figure 363. Viscosity-temperature relation for fuel oils (Reprinted by permission of the copyright owner, Esso Research and Engineering Co., Linden, N.J.).

The problem is almost always traceable to the same origins, that is, the burner and fuel are not compatible, or the burner is not properly adjusted or operated.

Oxidizable emissions depend upon the degree to which performance falls below the optimum capabilities of combustion equipment. Actual performance is, however, a difficult thing to predict. A survey (Chass and George, 1960) of gas- or oil-fired equipment in the Los Angeles area was made on this subject. Some 27 representative equipment items, ranging from a small water heater to an 870-hp boiler, were tested for combustion characteristics as well as air pollutants. No attempts were made to adjust the equipment before the tests; the data reflected, therefore, what can be considered normal operation.

Thirteen of the equipment items tested were fired alternately with both gas and oil, oil being the standby fuel. Four items were fired only with fuel oil and 10 only with natural gas. Natural gas is the predominant fuel in the test area. Curtailable gas users do not normally burn standby fuel more than 20 days in a given calendar year. During some winter seasons, small users have not been curtailed at all. Thus, oil burning was not an everyday occurrence in most of the gas- or oil-fired equipment tested.

The survey disclosed some points that would have been anticipated and others that would not. Table 143 summarizes emission factors developed from the data.

The most surprising indication was that the fineness of combustion control was much less when natural gas rather than fuel oil was used for firing. This was shown by the prevalence of carbon monoxide and the wide variation in fuel-air ratios during gas firing. In contrast, only negligible carbon monoxide was measured during fuel oil burning, and fuel-air ratios were held to much more constant figures. The same equipment found to emit appreciable carbon monoxide on gas firing discharged essentially no carbon monoxide (0.003%) when burning heavy fuel oil. In addition, combustion efficiencies were better when high-viscosity fuels (less than 17° API) rather than low-viscosity fuels (greater than 28° API) were burned. Apparently then, surveillance by the operator is a function of the complexity of burning the particular fuel. With a relatively easy-to-burn fuel such as natural gas, attentiveness can be expected to be minimal; while with high-viscosity oils, burner control will be most favorable. This phenomenon is probably peculiar to areas where natural gas is the predominant fuel and would be difficult to predict for other areas.

This situation may be due in part to the fact that smoke serves as a better alarm on oil firing. Smoke is likely to be emitted on oil firing when combustion is only moderately inefficient. An operator would be expected to notice visible emissions from the stack and make corrections at the burner. During gas firing, smoke does not occur unless combustion is markedly incomplete. A gas-fired burner can emit appreciable carbon monoxide without imparting perceptible opacity to products of combustion. Thus, a gas burner operator can well be ignorant of the fact that his equipment is not functioning efficiently.

As would be expected, the survey showed that emissions of particulate matter were appreciably higher during oil burning. Oil burning produced almost 10 times more particulates than natural gas burning did. There was little measured difference in particulate emissions between distillate and residual oil burning, even though the residual oils contained appreciably more inorganic ash.

In addition, the data showed, surprisingly, that distillate oils produced slightly greater quantities of aldehydes than residual oils did, probably because of the poorer combustion efficiencies encountered with light oils. Natural gas produced appreciably lesser aldehydes, even though combustion efficiencies in general were lower, as measured by the presence of carbon monoxide. During gas firing, high carbon monoxide values were generally accompanied by greater aldehyde

Table 143. EMISSIONS FROM GAS-FIRED AND OIL-FIRED EQUIPMENT (Chass and George, 1960)

Fuel burned	Items tested	Carbon monoxide			lb/equivalent barrel of fuel oil[a]			
					Particulate matter		Aldehydes as formaldehydes	
		Maximum, %	No. > 0.9%	No. > 0.09%	Range	Average	Range	Average
Natural gas	23	6.400	3	5	0.013 to 0.353	0.077	0.017 to 0.191	0.068
Light oil[b]	10	0.020	0	0	0.126 to 1.720	0.735	0.042 to 1.008	0.185
Heavy oil[c]	7	0.003	0	0	0.420 to 1.220	0.750	0.042 to 0.462	0.160

[a]If 6,000 ft^3 of natural gas is considered equivalent to 1 barrel of fuel oil.
[b]Light oils ranged from 28.7 to 45.1 API gravity.
[c]Heavy oils ranged from 8.0 to 16.5 API gravity.

concentrations. In no case, however, did aldehyde concentrations exceed 25 ppm (as formaldehyde) when natural gas was burned.

Ash and Sulfur Oxides

Stack discharges of sulfur oxides and ash are functions of fuel composition. During gas firing, both contaminants are well below nominal air pollution control standards. During oil firing, the inorganic ash content of combustion gases is normally less than 0.1 grain per scf, but sulfur oxide concentrations can be appreciable. Regulations limiting stack emissions of sulfur and the sulfur content of fuels have been enacted in several areas of the United States, as noted in the preceding part of this chapter. Regulations on particulate matter are aimed collectively at both inorganic ash and combustible solids. When excessive emissions are encountered during oil firing, carbon and other oxidizable particulates usually predominate.

Oxides of Nitrogen

Combustion processes as a group represent the major stationary source of oxides of nitrogen in most communities. Concentrations in products of combustion range from less than 10 to over 1,000 ppm by volume, measured as nitrogen dioxide. Concentrations appear to be a function of temperature and firebox design. The smallest concentrations are found at small appliances in which there is appreciable excess air at the burner. The largest concentrations are found in gases from the largest combustion sources--steam power plants, which are operated at high firebox temperatures. Combustion equipment of less than 20 million Btu per hour gross input does not normally emit NO_x in concentrations greater than 100 ppm. This subject is covered more completely in the next part of this chapter.

AIR POLLUTION CONTROL EQUIPMENT

Wherever control equipment is considered for combustion processes, it is almost always for controlling nonoxidizable materials, notably ash and sulfur oxides. If unburned and partially burned hydrocarbons or carbon particulates are the principal contaminants, the normal procedure is to increase combustion efficiency rather than collect these materials at the stack. An efficient burner is, therefore, the best and most inexpensive means of controlling combustible air contaminants. Control equipment has been proposed only for large combustion sources. To date, no satisfactory full-scale control devices have been installed on the principal type of objectionable equipment, steam power plant boilers, as indicated in the next part of this chapter.

BOILERS, HEATERS, AND STEAM GENERATORS

INTRODUCTION

Boilers, heaters, steam generators, and similar combustion equipment fired with fossil fuels are used in commerce and industry to transfer heat from combustion gases to water or other fluids. The only significant emissions to the atmosphere from this equipment in normal operation, regardless of the fluid being heated or vaporized, are those resulting from the burning of fossil fuels. Differences in design and operation of this equipment can, however, affect production of air contaminants.

A boiler or heater consists essentially of a burner, firebox, heat exchanger, and a means of creating and directing a flow of gases through the unit. All combustion equipment--from the smallest domestic water heater to the largest power plant steam generator--includes these essentials. Most also include some auxiliaries. The number and complexity of auxiliaries tend to increase with size. Larger combustion equipment often includes flame safety devices, soot blowers, air preheaters, fuel heaters, and automatic flue gas analyzers.

Inasmuch as coal is not used as boiler fuel in Los Angeles County, this discussion is limited to boilers, heaters, and power plant steam generators fired with gas or fuel oil.

Industrial Boilers and Water Heaters

The vast majority of combustion equipment is used to heat or vaporize water, or both. For convenience, industrial water heaters are considered together with boilers inasmuch as identical equipment is frequently used for both purposes. These boilers and heaters fall into three general classifications: Fire tube, water tube, and sectional.

Fire tube boilers constitute the largest share of small and medium-size industrial units, including the Scotch marine and firebox types, as shown in Figures 364 and 365. In fire tube boilers, the products of combustion pass through the heat exchanger tubes, while water, steam, or other fluid is contained outside the tubes. Many boilers such as these are sold as packaged units, with burners, blowers, pumps, and other auxiliaries all mounted on the same framework.

Water tube boilers are constructed in a wide range of sizes. Both the smallest and largest industrial units are likely to be of water tube design and, in fact, all large boilers (steam generators) are of this type. The smallest units are of simple box construction, commonly using tubing to circulate water and steam. In the water tube design

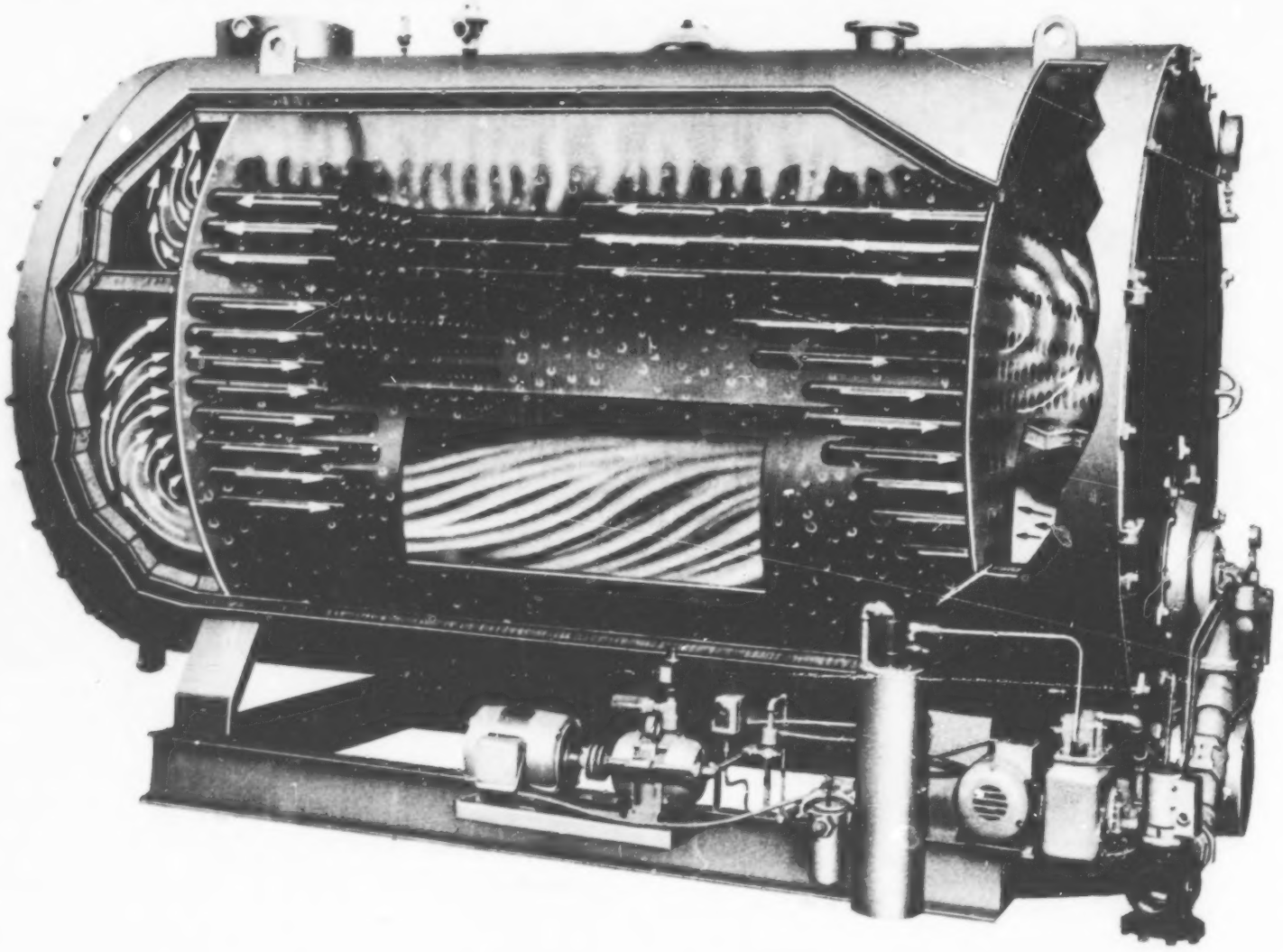


Figure 364. A three-pass, Scotch-marine boiler (Ray Burner Co., Boiler Division, San Francisco, Calif.).

shown in Figure 366, fluid is heated under pressure in a coil heat exchanger and flashed into steam in an external chamber. These relatively small, controlled-circulation boilers are capable of producing steam within minutes after a cold start. Industrial water tube boilers, such as that shown in Figure 367, are usually constructed with comparatively larger fireboxes than fire tube boilers have. In all water tube boilers, the water, steam, or heat transfer medium is circulated through the tubes while hot products of combustion pass outside the tubes.

Sectional boilers employ irregularly shaped heat exchangers and cannot be classed as either water tube or fire tube. Hot combustion gases are directed through some of these passages, transferring heat through metal walls to water or steam in the other passages. These units are manufactured in identical sections, such as those shown in Figure 368, which can be joined together according to the needs of the operator. A sectional boiler consists of one or more sections and can be enlarged or reduced by adding or removing sections. The heat exchanger assemblies are usually fabricated of cast iron. For this reason these boilers are not suitable for pressures greatly exceeding 15 psig. Cast iron sectional boilers find frequent use as water heaters and steam generators used in conjunction with space heating and laundries.

Power Plant Steam Generators

The largest boilers are located at steam power plants where high-pressure, superheated steam is used to drive turbo-electric generators. These water tube units are commonly termed steam generators. Nevertheless, there is no definite size limitation for equipment such as this, and steam generator designs do not differ markedly from those of many smaller industrial boilers.

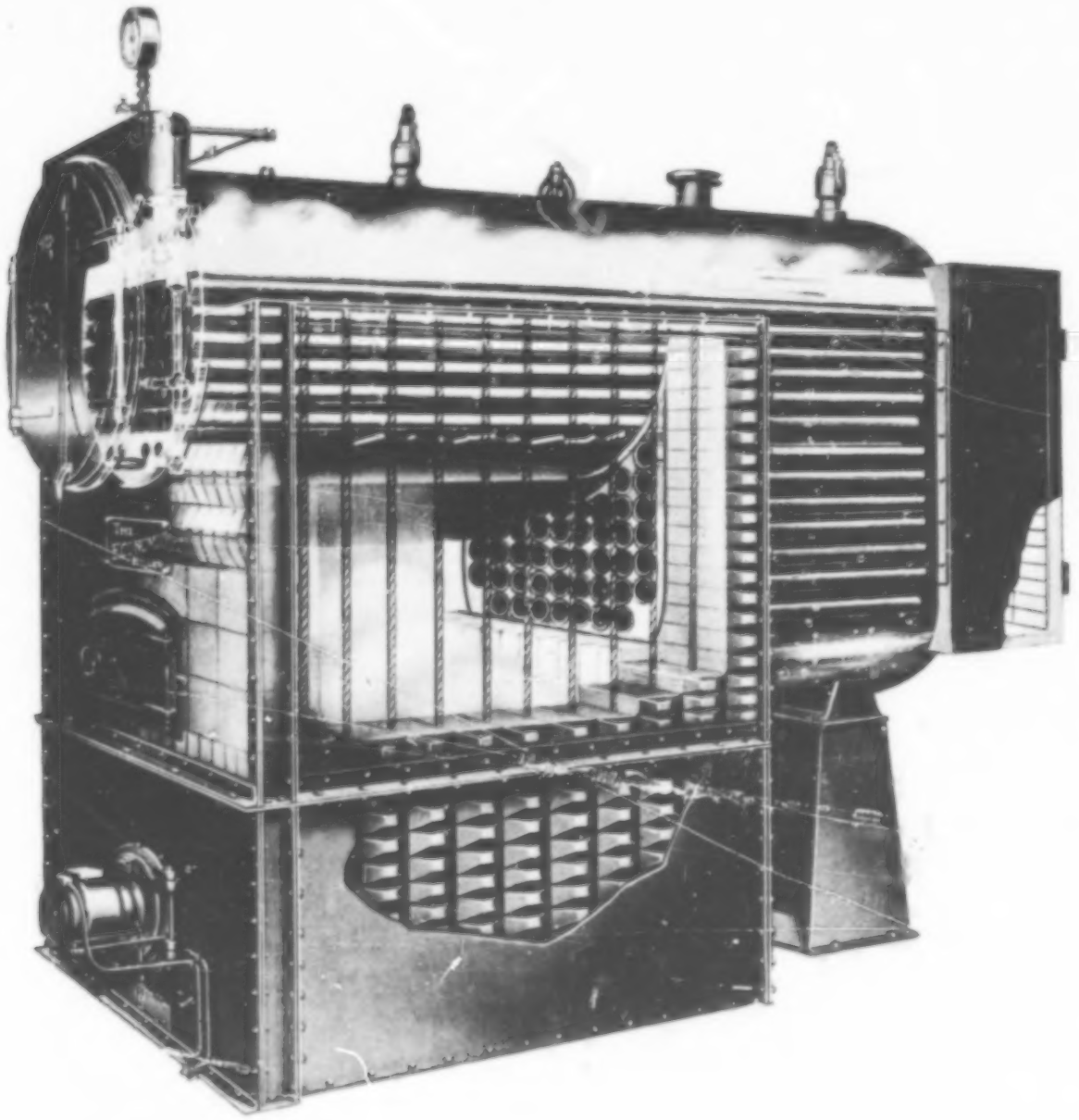


Figure 365. A fire-tube boiler with a refractory-lined firebox (Erie City Iron Works, Erie, Pa.).

Power plant steam generators produce from 50,000 to 5 million pounds of steam per hour at up to 2,500 psig and 1,000°F.

A typical large-city power plant steam generator consumes 2,500,000 cubic feet of natural gas per hour or 450 barrels of Number 6 fuel oil per hour, exhausts some 700,000 scfm combustion products and furnishes all the steam required to drive a 310,000-kilowatt electric generator. The trend toward large steam generators is illustrated in Figure 369.

A conventional front-fired power plant steam generator is shown in Figure 370. It is equipped with the full line of boiler auxiliaries: Air preheater, oil heater, economizer, superheater, and so forth. As much heat as is practical is extracted from combustion products. Stack temperatures are normally maintained at 225° to 320°F. Condensation and resultant corrosion are the principal deterrents to lower power plant temperatures. When exhaust gas temperatures approach the dew point, condensation and visible stack plumes are encountered.

Steam generators operate with thermal efficiencies of about 90 percent, and operating variables are more carefully controlled than in any other type of combustion equipment. Of prime concern is the excess air rate. Any air above the theoretical requirement represents a thermal loss, but the firebox oxygen concentration must nevertheless be sufficiently high to provide near perfect combus-

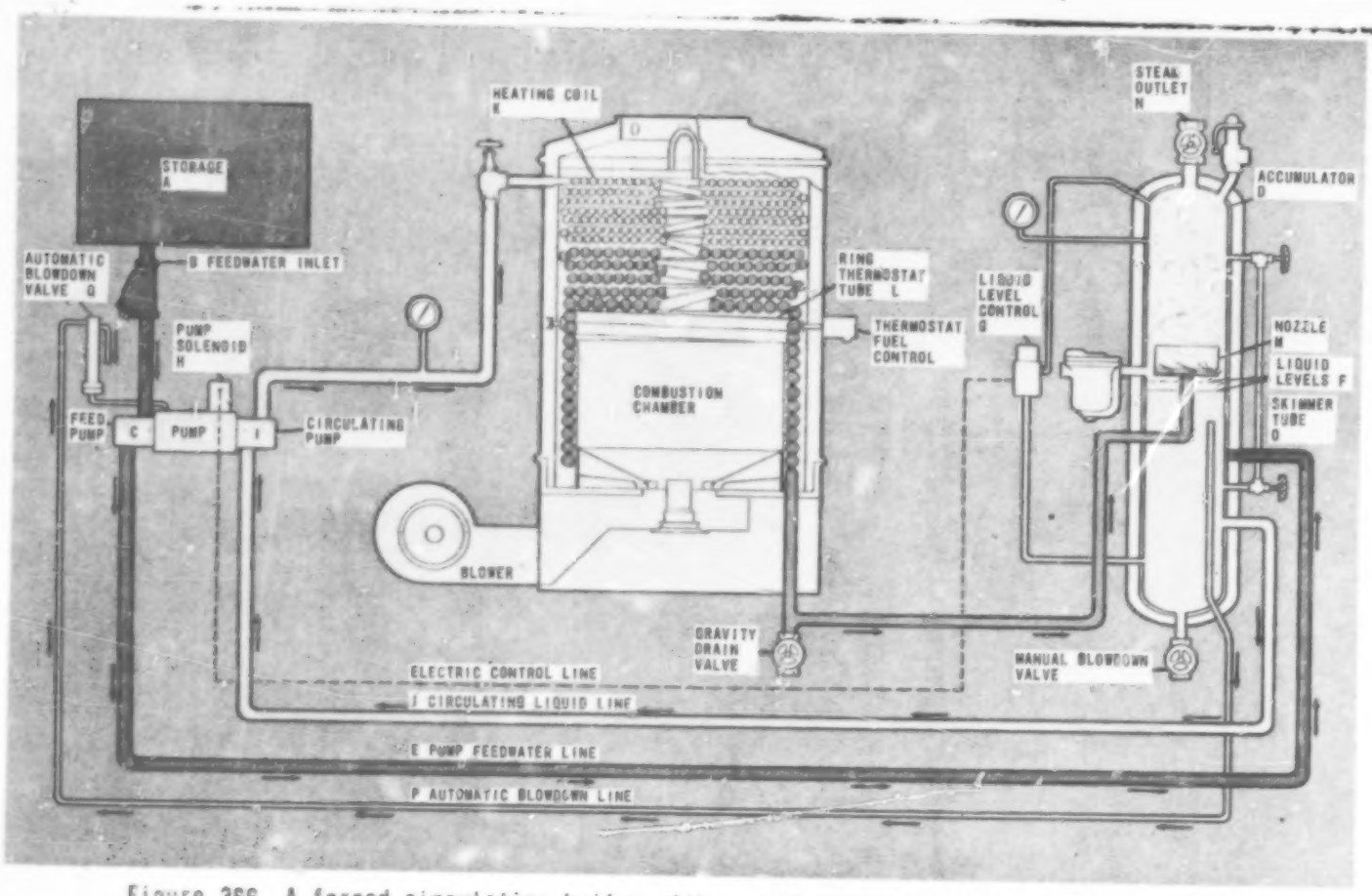


Figure 366. A forced-circulation boiler with a coil water tube heat exchanger and an external flash chamber-accumulator (The Clayton Manufacturing Co., El Monte, Calif.).

tion. Power plant operators hold excess air rates during fuel oil firing as low as feasible by providing strong mixing conditions and optimum fuel oil atomization at the burner. During gas firing, excess air rates are about 10 percent above the theoretical requirement. When fuel oil is burned, excess air is usually held below 15 percent. Attempts have been made to operate with excess air rates as low as 1 percent (about 0.2 percent oxygen) on oil firing (Glaubitz, 1963). The benefits from this practice are reduced corrosion, less air contaminants, and increased thermal efficiencies.

Refinery Heaters

Refinery oil heaters are noteworthy inasmuch as they usually comprise large combustion units and are likely to be fired with a wide variety of refinery by-product fuels, both gaseous and liquid. These fuels can be the least saleable refinery products, notably heavy residual oils and high-sulfur-bearing gas streams. The gaseous fuels are usually mixtures that for one reason or another, are not marketed or further processed. Typical analyses of refinery make gases are included in Table 139 on page 508. Note that they can contain appreciable amounts of sulfur, hydrogen, carbon monoxide, and higher molecular weight hydrocarbons. The latter are responsible for the relatively high heating values of refinery make gases.

Petroleum process heaters are apt to be fired with the highest viscosity oil fuels produced at a refinery. Residual fuel oils have traditionally been difficult to market; consequently, operators prefer to burn as much of these as possible in their own equipment.

In most refinery heaters, such as those shown in Figures 371 and 372, an oil or other petroleum product flows inside the heat exchange tubes. Fire tube oil heaters find only occasional use. These heaters, like all other refinery equipment, are normally operated 24 hours a day, 7 days a week. They are not likely to be shut down, except during periods of inspection and repair. Hot fuel oils are almost always available, and there is little likelihood of having to start a cold heater with unheated, high-viscosity fuel oil.

Hot Oil Heaters and Boilers

In a number of industrial combustion equipment units, a stable heat transfer oil is heated or

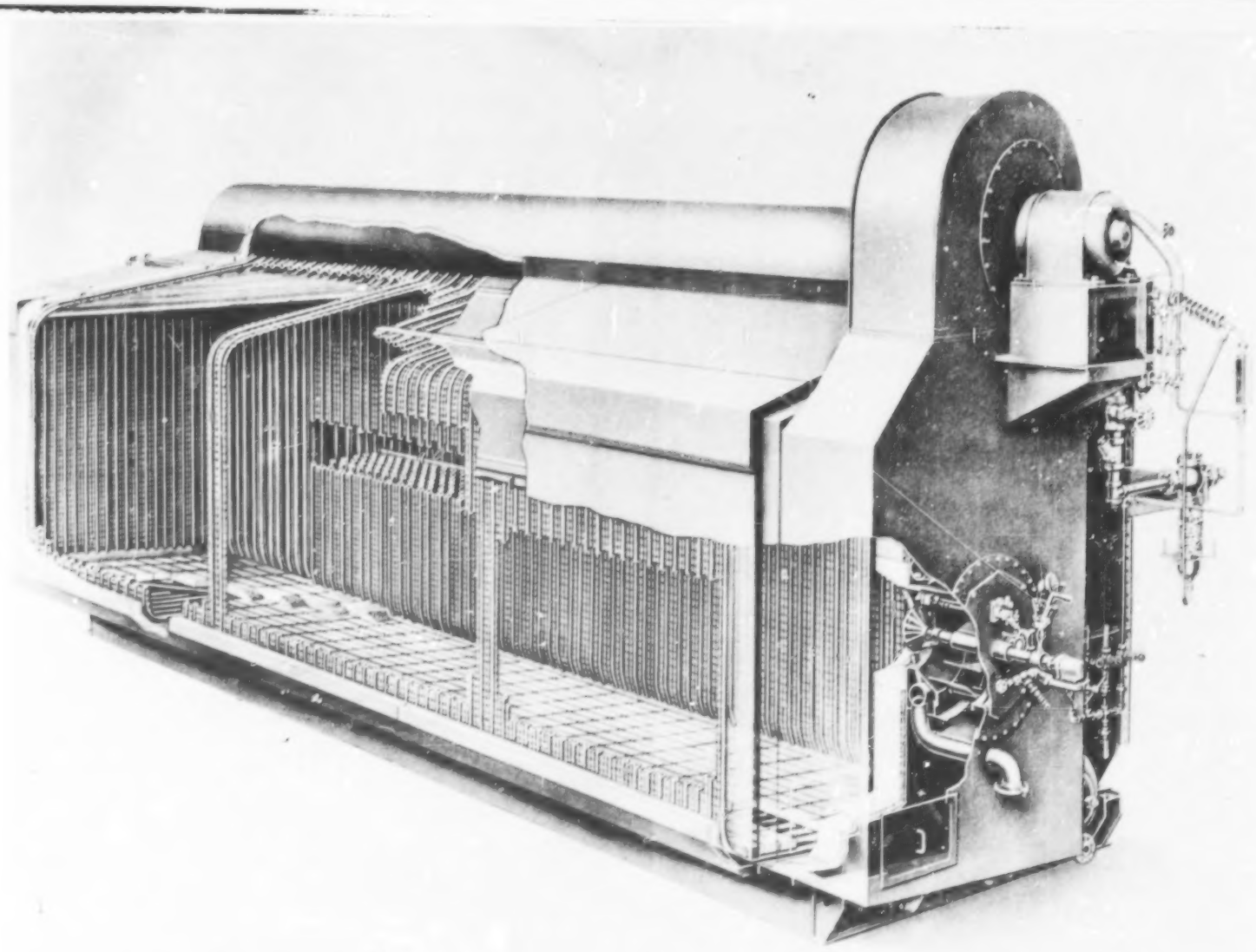


Figure 367. An industrial water tube boiler (The Babcock and Wilcox Co., New York).

vaporized. Some of these units are simple water tube boilers in which the heat transfer oil merely replaces water. Others are custom designed for the particular oil and application. These boilers, most often found in the chemical process industries, are used to transfer heat to another fluid in a heat exchanger device. Their principal advantage is the lower vapor pressures (higher boiling points) of the stable organic oils as compared with that of water. Most have boiling points between 300° and 800°F. In this range, the compounds, whether gases or liquids, exhibit markedly less vapor pressure than steam does at the same temperature.

The most common heat transfer medium is Dowtherm A,* a mixture of diphenyl and dipheny! oxide, with a boiling point of 495°F at 14.7 psia (Dow Chemical Co., 1963). A number of other oils are also marketed. Almost any liquid that is stable at the required elevated temperatures and has a suitable vapor pressure curve would be satisfactory for this use. Most of these materials are not highly toxic. Moreover, they are not emitted to the atmosphere in quantities sufficient to cause an odor nuisance or health hazard except for instances of equipment failure or gross disrepair. Some oils have sharp, penetrating odors that can be detected in the boiler room. These odors can be an annoyance to plant personnel.

*Registered Trademark of the Dow Chemical Company.

Fireboxes

Stack emissions from heaters and boilers are inherently tied to the fuels and burners, as noted in the preceding parts of this chapter. Of prime air pollution concern in the combustion equipment is the firebox in which the burners are located. Most fireboxes are constructed of such a shape and size that the burner flames are contained within the

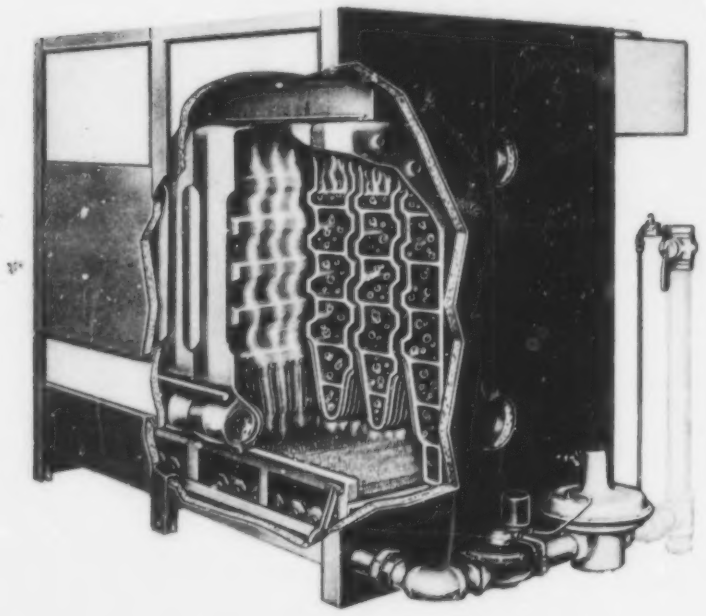


Figure 368. A cast iron sectional boiler (Crane Co., Johnstown, Pa.).

firebox and do not impinge upon the firebox walls or the heat exchange equipment. Flame impingement on either heat transfer surfaces or firebox walls usually results in incomplete combustion and a marked increase in air contaminant emissions.

The volume of the firebox is governed by the type of flame and the heat release rate. Where flames are luminous and relatively long, allowable heat release rates are low as compared with those of short, non-luminous flames. Clean, gaseous fuels can be burned at rates ranging up to 1 million Btu per hour per cubic foot of firebox volume. The latter rate is possible only with strong mixing conditions and necessarily high pressure drops across the burner. In practice, natural gas heat release rates of 100,000 Btu per hour per cubic foot and lower are more common. When oil is burned, even on a stand-by basis, heat release rates are always below the latter figure. The upper limit for burning low-viscosity fuel oils is about 100,000 Btu per hour per cubic foot of firebox volume. Heavy residual oils require greater combustion space. Design rates for residual-oil-fired combustion fireboxes range from 20,000 to 40,000 Btu per hour per cubic foot (The North American Manufacturing Company, 1952). Oil-burning heat release rates often govern firebox design, even though gaseous fuels may be burned in the equipment most of the time.

Most fireboxes of small and intermediate-size boilers and heaters are constructed of firebrick or refractory cement. Some are of metal construction, usually where firebox temperatures are relatively low. In large installations, the firebox, which is often termed here a furnace, is lined with water tubes or water walls through which cooling water is circulated. In these designs, water must be circulated at a sufficient

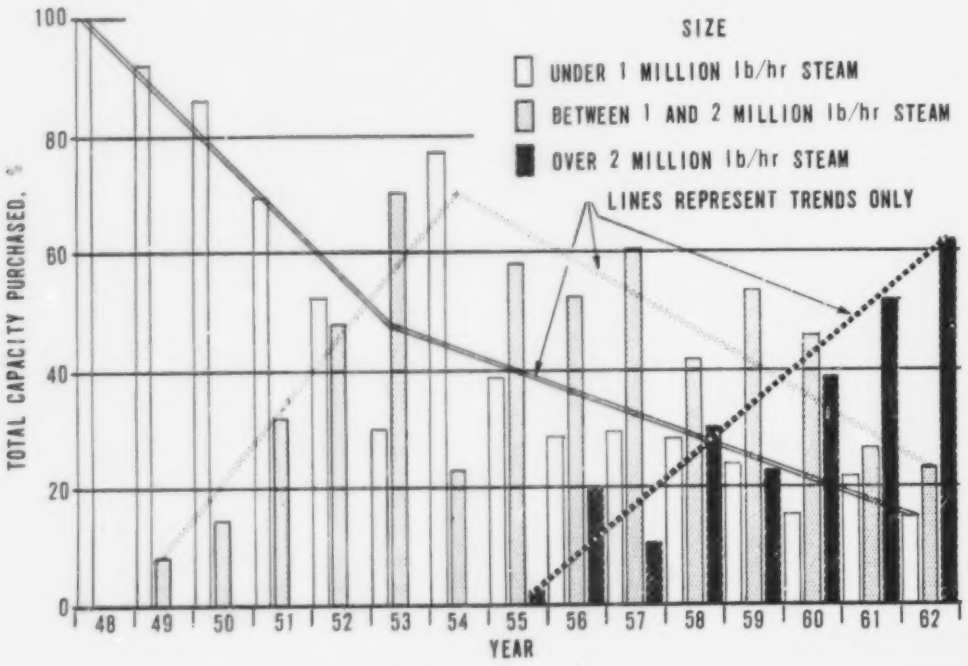


Figure 369. Percent of boilers of each size group purchased in the year ending April 30 (Frankenburg, 1963).

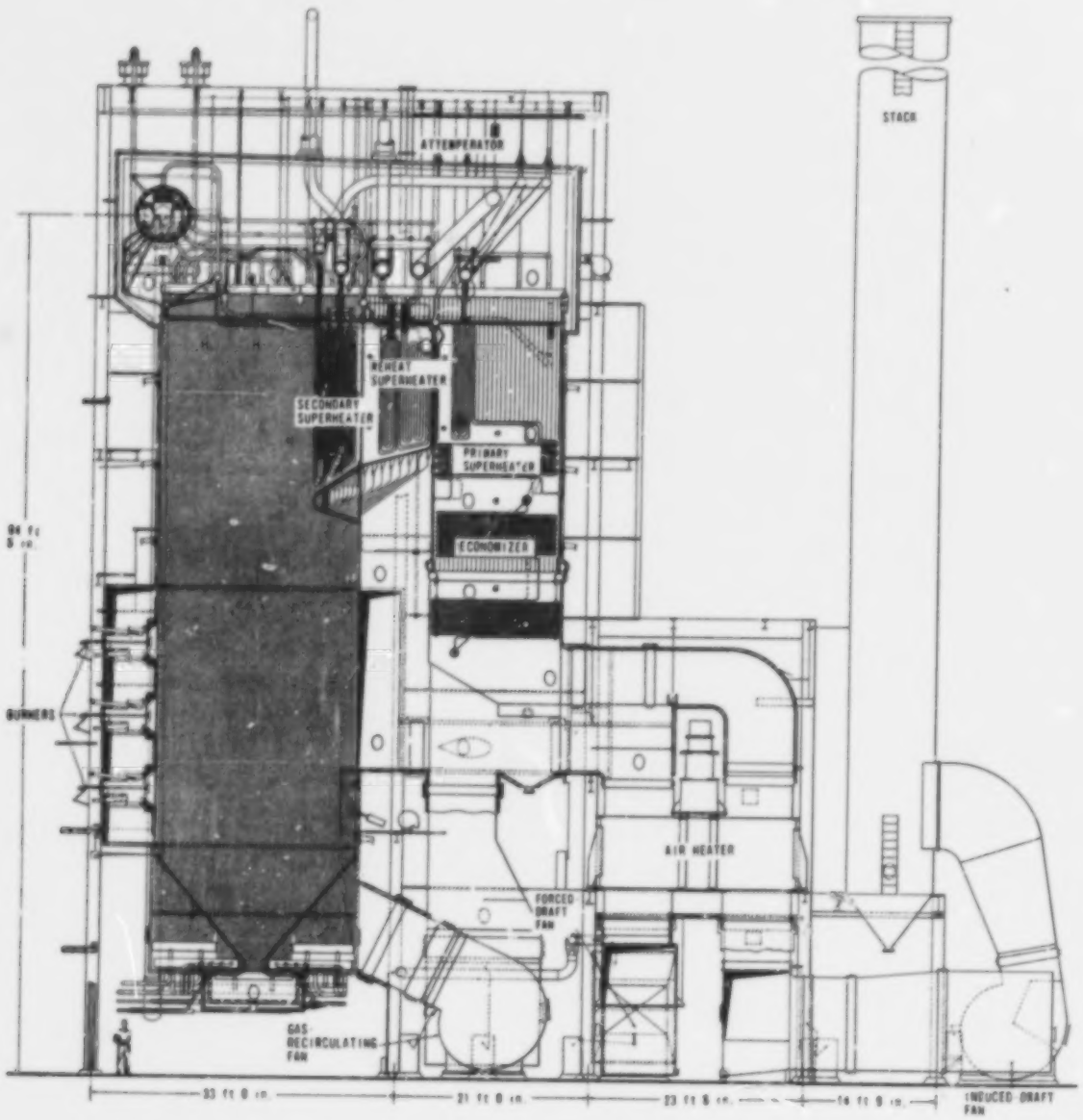


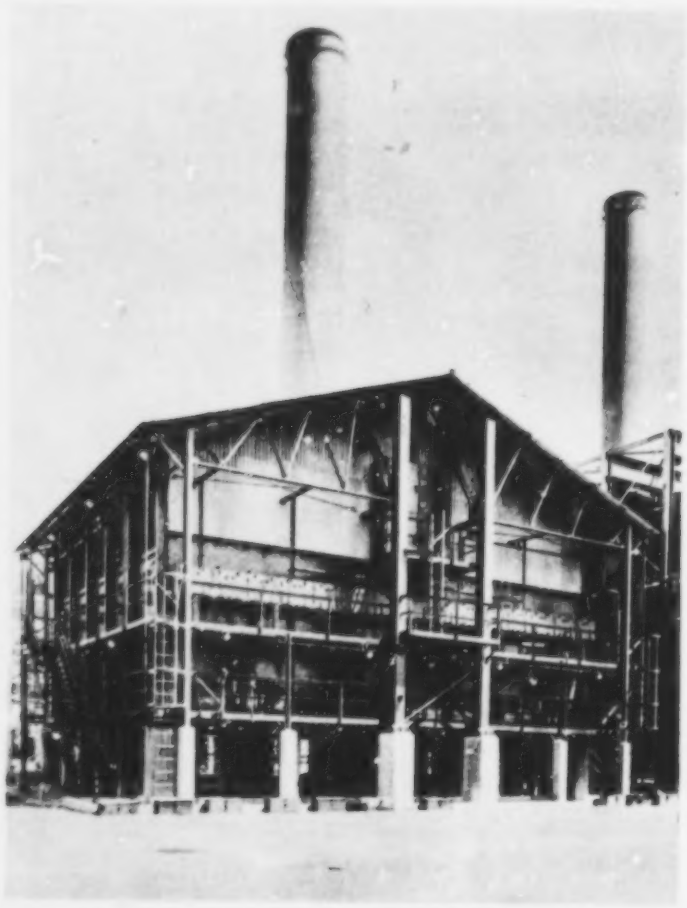
Figure 370. A front-fired power plant steam generator (The Babcock and Wilcox Co., New York).

rate to prevent heat damage to the metal walls or tubes. Much of the heat transfer in the furnace is by radiation rather than convection. Almost all large boilers, for example, steam generators at power plants, are constructed with water-tube-lined fireboxes.

Soot Blowing

Whenever fuels of measurable ash content are burned, some solids, including both carbon and inorganic ash, adhere to heat transfer surfaces in the combustion equipment. These deposits must be periodically removed to maintain adequate heat transfer rates. It is common practice to remove these deposits with jets of air or steam while the combustion equipment is in operation. The removed soot particulates are entrained in combustion gases. During periods of soot blowing, particulate concentrations are, as would be expected, considerably greater than during normal operation. Instantaneous particulate concentrations vary greatly during soot blowing because of the inherent operating characteristics of the lances.

A typical long retractable soot blower is shown in Figure 373. During operation the lance containing the air or steam jets rotates and moves horizontally across the tube surface. On the instroke, most of the particulates are removed. Consequently, stack emissions are heavier on the instroke than on the outstroke for a given lance. Normally, there are from 8 to 15 of these blowers on a large power plant's water tube boiler. The blowers are usually operated in sequence, by starting at the front or upstream tube surfaces and working downstream, finally cleaning the air preheater.



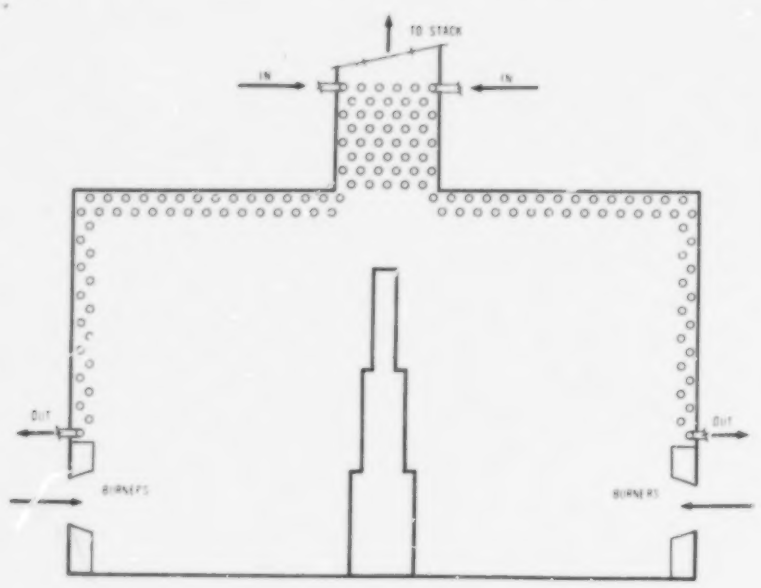


Figure 371. A large box-type refinery heater.

Whenever residual fuel oils or solid fuels are burned in large steam generators, tube cleaning is usually conducted at least once during every 24 hours of operation. When clean natural gas fuels are burned, the same boiler or heater can be operated indefinitely without soot blowing, except possibly for the air preheater. In fact, the burning of natural gas gradually removes materials deposited during oil firing. At many highly integrated power plant boilers, soot blowers are operated automatically, at 2- to 4-hour intervals. At many older installations, soot-blowing equipment is likely to be manual, the operation is time-consuming, and intervals between blowings comparatively longer. In the latter cases, particulates are somewhat larger and emissions during any one blowing are likely to be heavier in comparison with automated lancing operations. Where soot blowers are manually operated, the tubes are not usually cleaned more than once per 24 hours of oil firing.

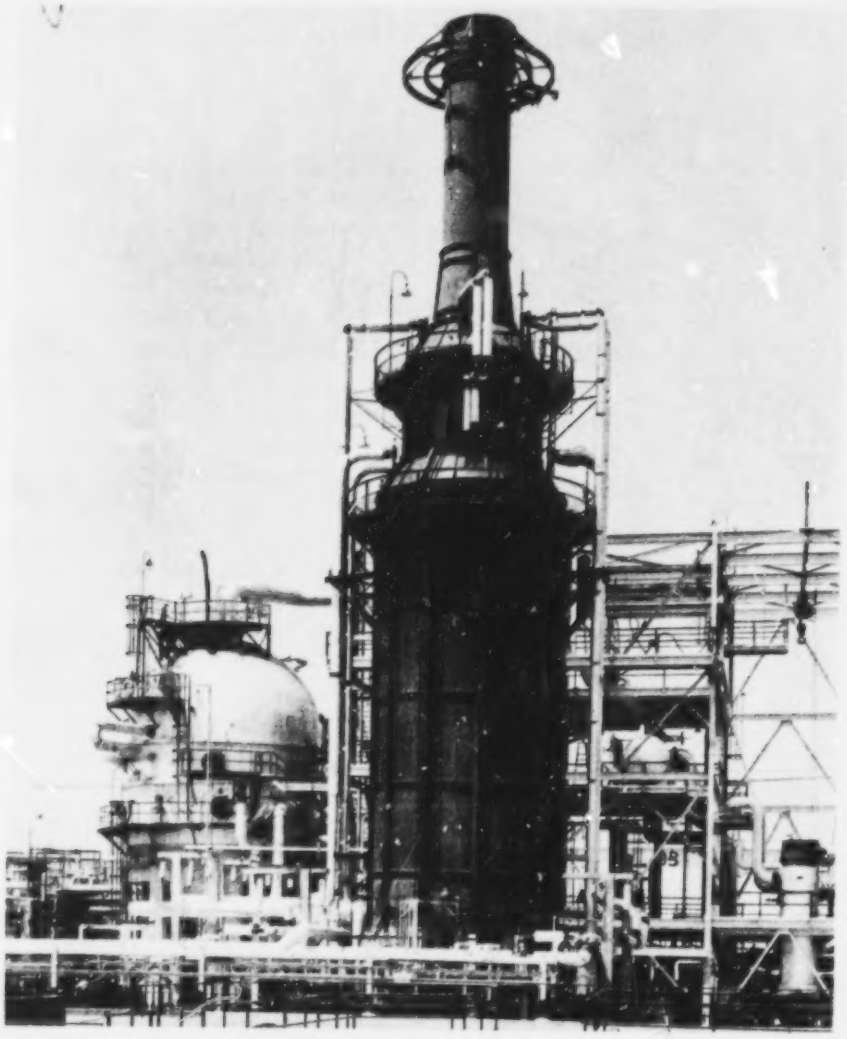
THE AIR POLLUTION PROBLEM

Air contaminants emitted from combustion equipment are described in the preceding parts of this chapter, covering fuels and burners. Nevertheless, the size and design of combustion equipment greatly affect the quality and quantity of stack emissions.

Most air contaminants in combustion equipment are formed in the firebox and are definitely influenced by firebox and burner design. Heat exchange surfaces are generally considered to have some catalytic effect on sulfur oxides and possibly oxides of nitrogen, but there are few data or little agreement on the extent of this influence. Tube surfaces, without question, affect pollutants in that they collect enough particulates to require lancing during periods of oil firing.

For the purpose of this discussion, the assumption is that the material being heated or vaporized in the heat exchanger tubes is not a significant source of air pollution. This is, in fact, the situation with common combustion equipment. A major odor nuisance or health hazard can, however, be caused by venting organic vapors to the atmosphere, though this would be expected to occur only during equipment breakdown. That an operator would purposely jettison significant quantities of his product or of expensive heat transfer fluids is not likely.

Combustion equipment emits both visible and nonvisible air contaminants. Visible contaminants are principally liquid and solid particulates. Nonvisible contaminants include nitrogen oxides, carbon monoxide, and sulfur dioxide. A material that straddles both categories is sulfur trioxide, the extremely hygroscopic anhydride of sulfuric acid.



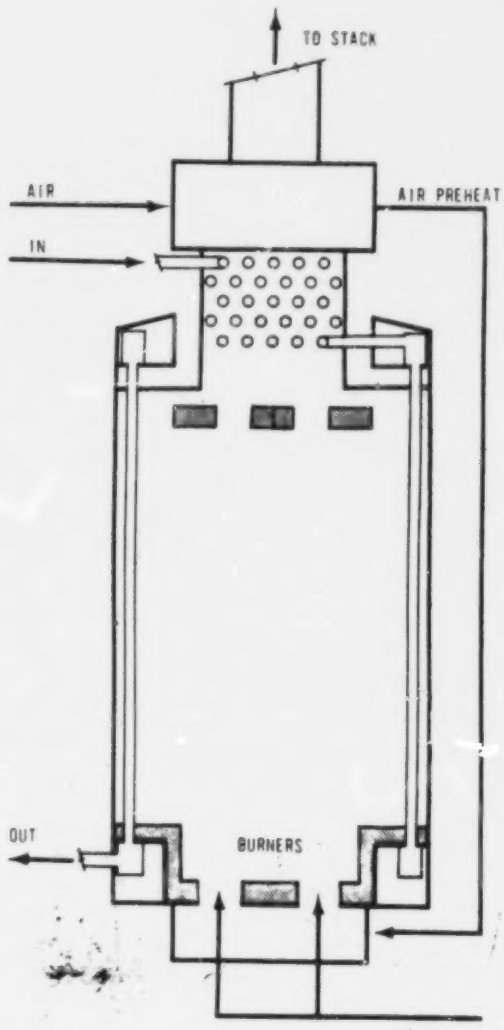


Figure 372. A vertical, cylindrical refinery heater (Union Oil Co., Los Angeles, Calif.).

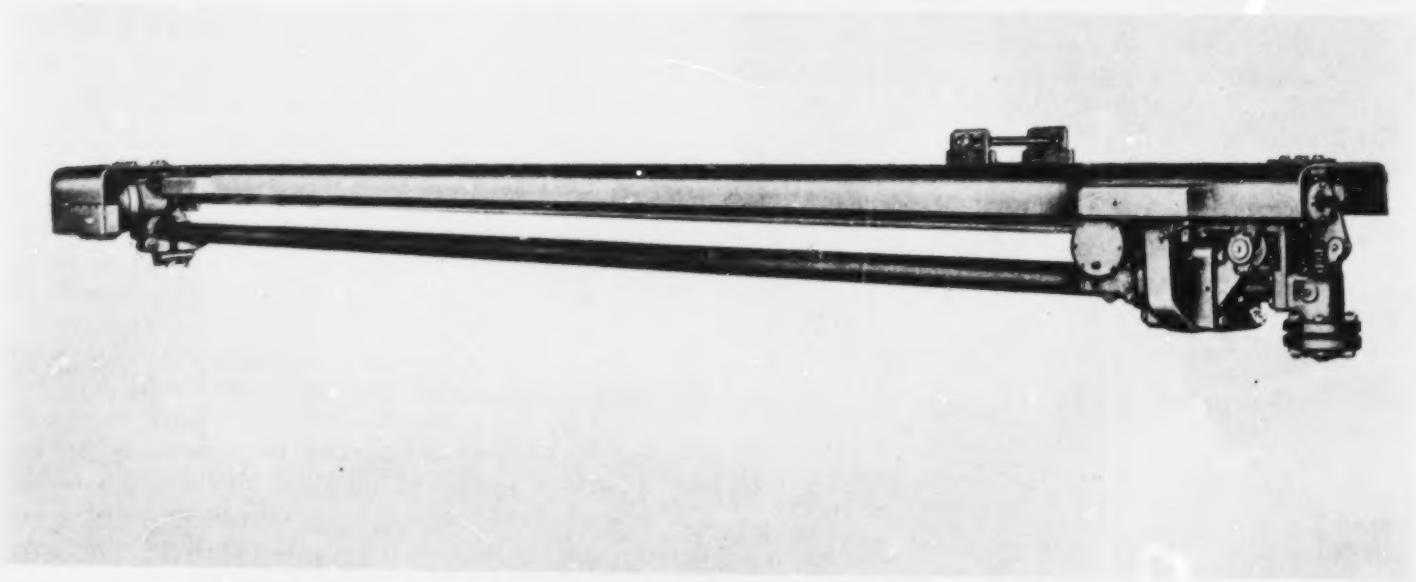


Figure 373. A long-travel retracting soot blower with an air motor drive (Diamond Power Specialty Corp., Lancaster, Ohio).

Solid Particulate Emission During Normal Oil Firing

Where combustion is most nearly complete, inorganic ash constitutes the principal particulate emission. The inorganic ash contents of most fuel oils and all gaseous fuels are normally well below the concentrations that would cause excessive particulate emissions. As noted in the first part of this chapter, an inorganic ash content of 0.1 percent in typical residual fuel oil results in a stack concentration of only 0.03 grain per scf at 12 percent carbon dioxide. Particulates from residual-oil firing are considerably larger than those emitted during gas firing, as can be seen in Figures 374 and 375. Nevertheless, particulates from oil burning are still principally in the submicron range and are in sufficiently large concentration to cause perceptible light scattering. Finely divided ash is considered a contributor to visible stack plumes at a large power plant's steam generators. Most of this material is in the form of metal oxides, sulfates, and chlorides. A spectrographic analysis of a typical residual oil ash is presented in Table 142.

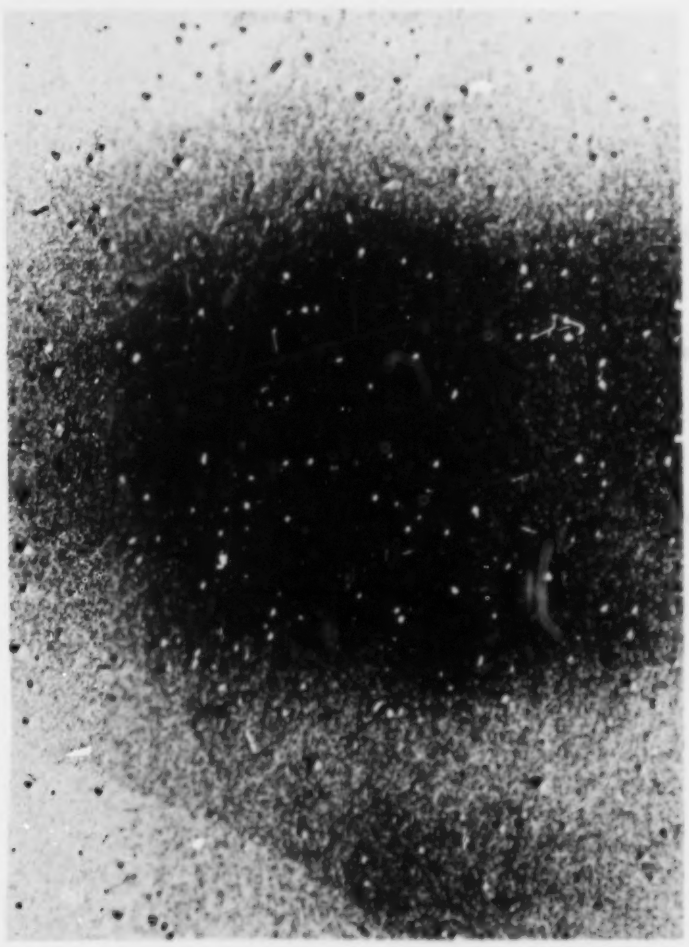


Figure 374. Photomicrograph of particulates collected during gas burning. 18,000X.

Figure 375. Photomicrograph of particulates collected during oil burning. 18,000X.

As shown in Table 144, over 85 percent of the particulates are less than 1 micron. More than 98 percent are smaller than 5 microns. These data pertain only to equipment in which combustion is most nearly complete and where little carbon or hydrocarbon is present in the ash. If appreciable amounts of carbon were present, particles would be larger and possibly of different shapes.

From this particle size distribution, two conclusions can be drawn: (1) visible opacities are higher than would be the case if particles were noticeably larger than 1 micron since maximum light scattering occurs at about 0.7 micron; (2) centrifugal dust collectors are not effective in removing particulates from the gas stream. High-efficiency centrifugal collectors are not efficient in removing particulates of less than 5 microns and are only moderately so in the 5- to 10-micron range.

Typical regulations limiting airborne particulates from combustion equipment allow a maximum of 0.3 grain per scf at 12 percent carbon dioxide (Rule 53b of the Los Angeles County Air Pollution

Table 144. PARTICLE SIZE DISTRIBUTION OF TYPICAL MATERIAL COLLECTED FROM A STEAM GENERATOR STACK DURING THE BURNING OF RESIDUAL FUEL OIL

	% in each micron range				Largest particle size, μ
	0 to 1	1 to 2	2 to 5	>5	
Absolute filter	86.6	7.3	4.2	1.9	50
Millipore filter	88.5	7.3	2.3	1.9	50

Control District Rules and Regulations). This includes combustible particulates as well as inorganic ash. This limit may be exceeded when common hydrocarbon gases or fuel oils are burned if appreciable amounts of carbon or carbonized high molecular weight hydrocarbon materials, or both are present. The latter situation results from either poor operation or incorrect selection of burner and fuels. In these instances, the resulting visible contaminants at the stack are black, and are apt to exceed allowable limits, most of which are based on the Ringelmann Chart.

The shapes of carbon or combustible particulates vary somewhat with fuels and operating conditions. If a light fuel oil or gaseous fuel is burned in a deficiency of oxygen, the resulting carbon particles are likely to be exceedingly fine. If, on the other hand, these contaminants are the result of burning heavy fuel oil with improper atomization, the carbon particles emitted are likely to be in the form of cenospheres, as depicted in Figure 376. Cenospheres are spherical, hollow particles, essentially the same as those produced during spray drying. Cenospheres have appreciably smaller bulk densities than solid particulates do (MacPhee et al., 1957).

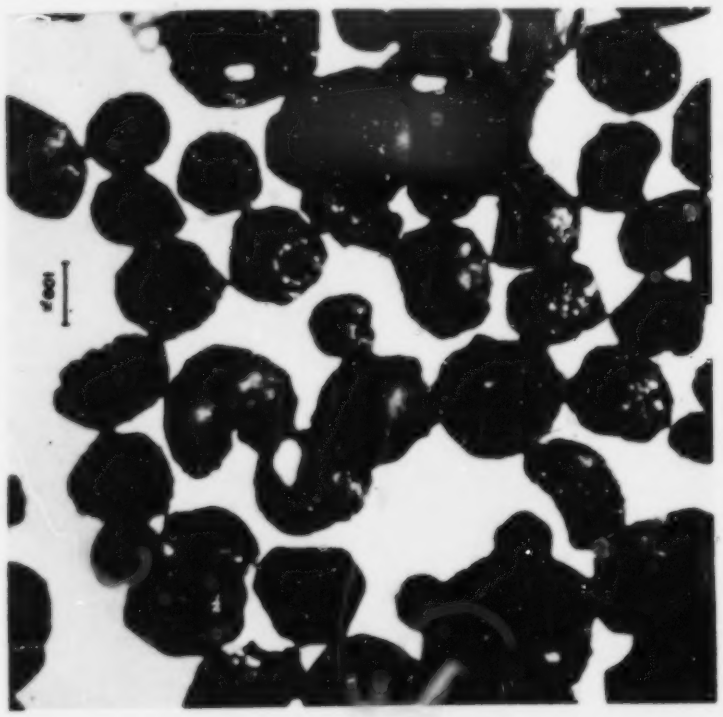


Figure 376. Photograph with light microscope of cenospheres found in breeching of large oil-fired steam generator (MacPhee, 1957).

An operator is not likely to want to discharge carbon in either form, or to have to control these particulates at the stack. When there is evidence of appreciably unburned particulates in combustion gases, steps should be taken to improve combustion at the burner. With high-viscosity oils, these steps can consist of using lower viscosities or increasing pressure drops across the burner to provide proper atomization.

Soot-Blowing Particulates

At times when soot blowers are in operation, particulate matter concentrations in exit gases increase markedly. Instantaneous concentrations depend upon the dirtiness of tube surface and upon the rate at which the lance moves across the tubes. Soot-blown air contaminants can impart excessive opacities to stack gases and cause damage by acidified particulate deposition in immediately adjoining areas. The air pollution potential, in terms both of opacity and nuisance, increases with the time interval between soot-blowing operations. Where tubes are blown at 2- to 4-hour intervals, as is done on many modern combustion devices, there is little increase in the opacity of stack emissions, and the small sizes of particulates as well as the relatively small concentration reduce the possibility of fallout damage. Intervals of 8 hours and longer between tube lancings can result in excessive visible opacities as well as fallout damage.

Soot-blowing air contaminants are not considered to be highly significant in the overall air pollution of a given area, inasmuch as they are emitted only for relatively short intervals and tend to settle close to the source. They represent less than 10 percent of the total particulates emitted from an oil-fired boiler. Many operators avoid technical opacity violations by special scheduling of soot-blowing operations. This involves either more frequent lancing or the lengthening of the total operation. Neither course reduces overall air pollution, but both can allow technical compliance with air pollution control regulations involving permitted opacities.

Sulfur Dioxide

As pointed out in the first part of this chapter, practically all fuel-contained sulfur--upwards of 95 percent--shows up in exhaust gases as sulfur dioxide, a colorless gas. There is no way of preventing the formation of sulfur dioxide, and con-

centrations are functions of the fuel's sulfur content. As undesirable as sulfur dioxide is, it is, nevertheless, generally considered less obnoxious than sulfur trioxide and the odorous sulfides and mercaptans contained in the fuel.

Sulfur Trioxide

Up to 5 percent of the total fuel's sulfur is converted to the higher oxide, sulfur trioxide, in large combustion equipment. The volume of sulfur trioxide found in gases from power plant steam generators (5 to 50 ppm) is considered to be a principal cause of the visible plume often present during oil firing. It readily combines with water to form sulfuric acid and, as such, can cause acid damage in downwind areas.

The oxidation of sulfur is considered to proceed in two steps as follows:

$$S + O_2 \rightleftharpoons SO_2$$

$$SO_2 + 1/2\ O_2 \rightleftharpoons SO_3.$$

As shown in Figure 377, equilibrium at ambient temperatures strongly favors sulfur trioxide rather than the dioxide. At elevated temperatures, the dioxide predominates. The reaction rate falls off rapidly, however, below 700°F; as a result, the major portion of the fuel's sulfur is still in the dioxide form when discharged from combustion equipment.

As might be expected, the degree of sulfur trioxide formation in combustion equipment varies widely. Concentrations are negligible in small equipment, even when fired with high-sulfur fuel oils. As equipment sizes and firebox temperatures increase, sulfur trioxide concentrations increase appreciably though seldom exceeding 35 ppm. Heaviest emissions are found at the largest combustion sources--power plant steam generators.

Formation of sulfur trioxide appears to depend upon several factors. Concentrations tend to increase with increases in firebox temperatures and oxygen concentrations. In addition, oxida-

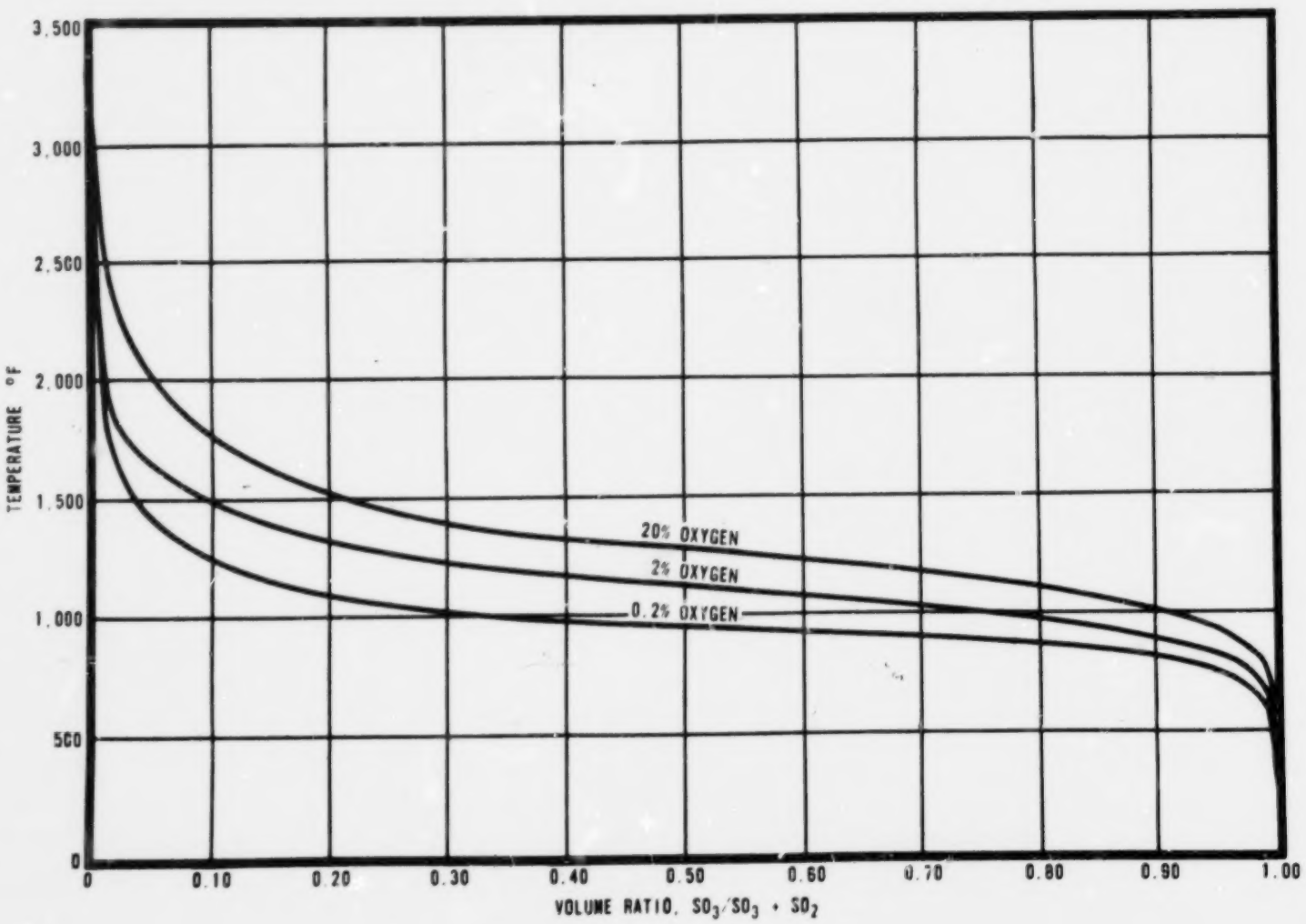


Figure 377. Equilibrium concentrations of SO_3-SO_2 at various oxygen concentrations as per the reaction $SO_2(g) + 1/2\ O_2(g) = SO_3(g)$. (Adapted from Hougen and Watson, 1945).

tion catalysts such as vanadium, iron, and nickel oxides tend to increase SO_3 production. Particulates that adhere to tube surfaces usually contain appreciable quantities of all three of these catalytic materials.

Crumley and Fletcher (1956) ran a series of experiments on a small kerosene fuel furnace from which they concluded that, for a given total sulfur oxide (SO_2 + SO_3) concentration:

1. SO_3 formation increases as flame temperatures are increased up to about 3,150°F;
2. above 3,150°F, SO_3 formation does not increase, that is, the SO_3/SO_2 rate remains constant;
3. when flame temperatures are held constant, SO_3 formation decreases as the excess air rate is reduced;
4. SO_3 formation decreases with coarser atomization. This phenomenon may be a result of lower flame temperature.

The work of Glaubitz (1963) generally agrees with these conclusions regarding small oxygen concentrations at the burner. It is discussed later in this chapter.

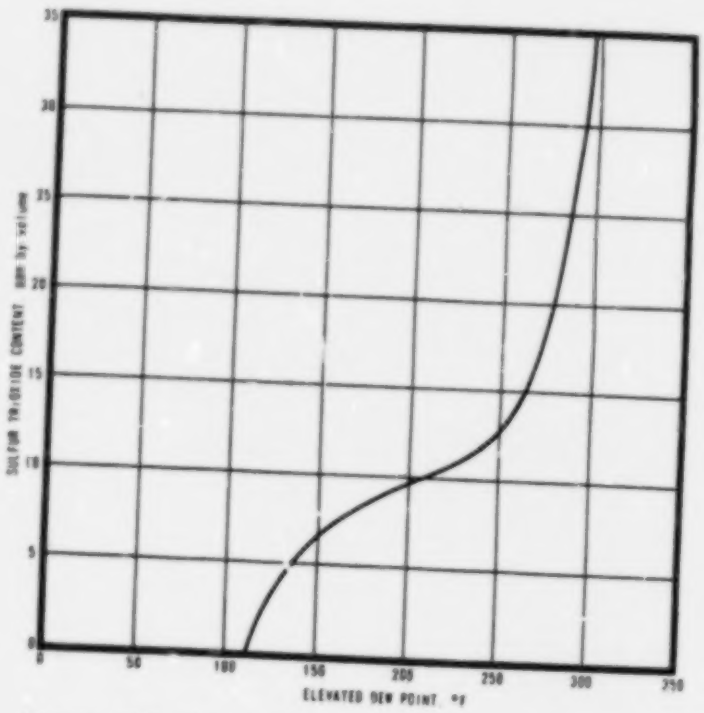


Figure 378. Dew point elevation as a function of sulfur trioxide concentration (Adapted from Rendle and Wilsdon, 1956).

Sulfur trioxide is considered the principal cause of the visible plumes emitted from power plant steam plant generators. It apparently unites with moisture in the air and with flue gases to form a finely divided sulfuric acid aerosol. Droplet condensation may be enhanced by the presence of particulate matter, which provides condensation nuclei.

These visible emissions are interrelated with so-called dew point raising. The presence of sulfur trioxide and sulfuric acid effectively results in a gaseous mixture that appears to have a dew point higher than would be predicted solely on the basis of the moisture content. These dew point elevations can exceed 200°F. Figure 378 shows typical dew points and sulfur trioxide concentrations measured at an experimental oil-fired furnace (Rendle and Wilsdon, 1956). Note that sulfur trioxide, in concentrations ranging from 5 to 25 ppm by volume, increases the dew point (about 115°F based upon H_2O alone) by increments of 20°F and 170°F respectively. There are noticeable differences in published values of dew point elevation. These are attributable in part at least to the difficulties encountered in SO_3 analysis.

Sulfur trioxide has a further disadvantage in that it tends to acidify particulate matter discharged from combustion equipment. This is commonly evidenced by acid spotting of painted and metallic surfaces, as well as of vegetation in the downwind area Acid damage is usually the result of discharge of particulates during soot blowing.

Excessive Visible Emissions

Combustion equipment has traditionally been associated with visible smoke plumes caused by unburned carbon and organics. With modern steam generators, markedly incomplete combustion is a relative rarity. Combustible air contaminants are seldom present in sufficient concentrations to obscure visibility. Nevertheless, visible plumes of greater than 40 percent opacity are common at large oil-fired steam generators where there are only minimal quantities of unburned materials in exhaust gases. These opaque emissions are commonly attributed to finely divided inorganic materials, notably sulfur trioxide and inorganic particulates.

The formation of visible plumes in stack gases that are practically devoid of unburned carbonaceous materials is not fully understood. The phenomenon is known to occur only when there is appreciable sulfur in the fuel and when the steam generator is of relatively large capacity greater than about 60,000 pounds of steam per hour. The plumes do not occur during the burning of "clean" natural gas, that is, gas with only sufficient sulfur to impart a detectable odor--about 0.15 grain per 100 cubic feet of gas. With fuel oils of 0.3 to 0.5 percent sulfur, some visible emissions can occur at the stack, but opacities do not usually exceed 40 percent. At smaller power plants, that is, those with a capacity of 50,000 to 500,000 pounds of steam per hour,

the opacity of exhaust gases does not normally exceed 30 percent when the plant is fired with residual oil of average sulfur content, namely 1.4 to 2.0 percent. Steam generators of 750,000 pounds per hour and greater ratings can be expected to emit gases of heavier than 40 percent opacity when fired with oil of more than about 1.0 percent sulfur.

Figure 379 illustrates the difference in visible emissions from two identical side-by-side steam generators on oil and gas firing. Both are rated at 1,200,000 pounds of steam per hour and are of conventional front-fired design. Stack temperatures were approximately 300°F. The unit on the left was being fired with natural gas, and there was no detectable opacity in the exhaust gases. The identical unit on the right was being fired with fuel oil of approximately 1.6 percent sulfur and was discharging gases of approximately 80 percent opacity. The visible plume from an oil-fired unit such as this normally varies from white to brown, depending upon weather conditions and the makeup of particulate matter. In some cases, the visible plume appears to be detached from the stack. The gas stream immediately above the stack outlet is clear or at least of low opacity but becomes opaque further downstream. Apparently, cooling in the immediate stack discharge area lowers temperatures below the dew point, causing formation of extremely fine sulfur trioxide and acid droplets.

There is some difference of opinion as to the cause of this plume, but all evidence points to sulfur trioxide as the principal determinant, with particulate matter as a possible contributor. Observations have been made with residual fuel oils of varying sulfur content. In general, the fuels containing greater percentages of sulfur were found to produce heavier opacities. Since low-sulfur oils also have lower ash contents, there is less particulate matter in stack gases during the burning of low-sulfur fuels as evidenced when opacities are lowest.

Stack opacities could conceivably be reduced if the inorganic particulate sizes were increased above the submicron level. With an arrangement such as this, there would be an appreciably smaller number of submicron particles in a given volume of stack gases. No satisfactory method of increasing particle sizes has, however, been developed for residual oil. The most obvious method--coarser atomization--would result in increased combustible particulates that would possibly be more undesirable than the visible plume.

Some trials have been made by injecting sulfur trioxide into the relatively clean stack gases from natural gas firing. These experiments indicate that definite visible opacity can be imparted at concentrations of 5 ppm SO_3 by volume and greater. Stack gases with 5 ppm SO_3 had an opacity of approximately 20 percent. An opacity of approximately 50 percent resulted when the SO_3 concentration was increased to 15 ppm. The test unit was a 1,200,000-pound-per-hour steam generator from which there was no visible plume during normal gas firing. The stack gases during SO_3 addition appeared white when viewed with the sun at the rear of the observer and were not unlike plumes discharged from the same unit during oil firing.

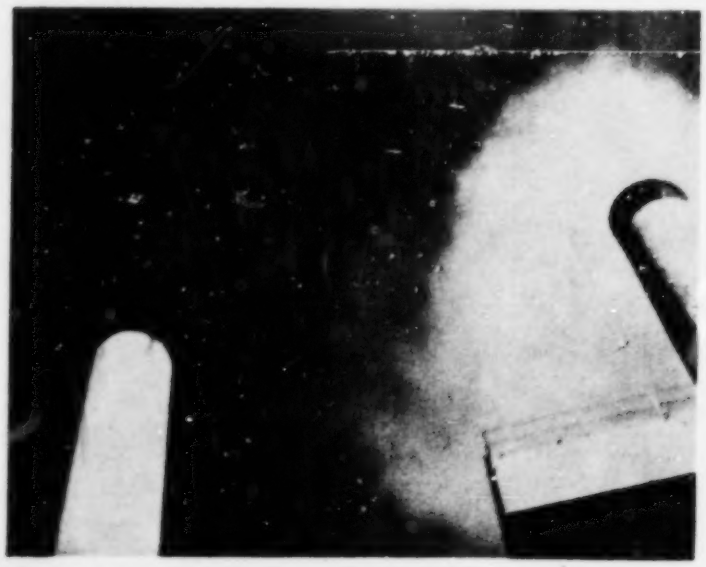


Figure 379. Exhaust gases from identical steam generators showing visible plume from oil-fired unit (right) as compared with clear stack of gas-fired unit (left).

There is evidence that "dirtiness," that is, accumulation of deposits on tube surfaces, also contributes to opacity. Identical side-by-side steam generators have been observed to emit gases of markedly different opacity when fired at the same rate with the same fuel oil. Invariably, the unit with the thicker tube deposits is found to emit heavier visible emissions and to contain considerably larger SO_3 concentrations. This phenomenon indicates that tube deposits are effective in catalytically oxidizing SO_2 to SO_3. The deposits that contribute to the "dirtiness" apparently are not sufficiently removed by normal soot-blowing procedures. To lower opacities and SO_3 emissions effectively, one should wash the tube surfaces with an aqueous solution. The cleaning of heat exchanger surfaces in this manner requires that the unit be shut down and allowed to cool beforehand. At most electric power stations, steam generators cannot be taken out of service often. Consequently, tube washing is a relatively infrequent occurrence.

Oxides of Nitrogen

Combustion equipment collectively represents the largest nonvehicular source of oxides of nitrogen air contaminants in most industrial areas. In Los Angeles County, where there is a high motor vehicle density, boilers and heaters are still responsible for more than 30 percent of the total oxides of nitrogen discharged to the atmosphere and for more than 90 percent of the total from all stationary sources (Los Angeles County Air Pollution Control District, 1963).

Exhaust gas concentrations of oxides of nitrogen range from less than 10 ppm by volume for small gas-fired water heaters to over 1,000 ppm for large power plant steam generators. Since both concentrations and gas volumes increase with size, power plant steam generators are always large sources of NO_x. These generators are much more significant in the overall air pollution picture than the markedly larger number of smaller domestic and industrial heaters and boilers are. One of these generators can emit over 2,000 pounds of oxides of nitrogen per hour. As shown in Table 145, there is a wide variation in NO_x emissions, even from equipment of the same general type and size.

Emissions of oxides of nitrogen from combustion equipment result from fixation of atmospheric nitrogen in the fireboxes. The principal high-temperature reaction is the formation of nitric oxide as follows:

$$N_2 + O_2 \rightleftharpoons 2NO.$$

Much of the nitric oxide formed in fireboxes is eventually further oxidized to nitrogen dioxide by the following mechanism:

$$NO + 1/2\ O_2 \rightleftharpoons NO_2.$$

The latter reaction reaches a maximum at about 600°F and is extremely slow at ambient temperature. Nitrogen dioxide is considerably more reactive than nitric oxide, and is a more obnoxious air contaminant.

A number of other oxides of nitrogen are also formed to lesser degrees. These include N_2O, N_2O_4, N_2O_5, and NO_3 and are not considered to be emitted in significant amounts. For purposes of this discussion, all oxides of nitrogen are considered collectively under the term NO_x. In the quantitative analysis of oxides of nitrogen, all oxides are commonly oxidized to the dioxide. Results are reported in concentrations of NO_x as NO_2.

At ordinary temperatures, fixation does not proceed to any measurable extent, but the reaction rate and equilibrium concentrations increase markedly with temperature. In Figure 380, equilibrium concentrations of nitric oxide are plotted over ranges of temperature and oxygen concentrations found in combustion equipment. Obviously, 100 ppm NO corresponds to equilibrium at about 1,800°F for the oxygen contents found in high-efficiency combustion gases, namely, 2 to 3 percent oxygen. At 3,000°F, equilibrium concentrations of NO are well over 1,000 ppm, even at 1 percent oxygen. Calculated flame temperatures are in excess of 4,000°F at 10 percent excess air (about 2 percent oxygen) for both oil and gas firing when air preheated at 600°F is used.

Table 145. EMISSIONS OF OXIDES OF NITROGEN FROM INDUSTRIAL BOILERS AND HEATERS
(Mills et al., 1961)

Source	Heat input range, millions of Btu/hr	Range of NO_x conc in flue gases, ppm by vol	Avg NO_x conc, ppm by vol	NO_x emission factors, avg lb per million Btu
Small oil heaters	Less than 60	20 to 100	47	
Natural gas				0.06
Fuel oil				0.33
Large refinery heaters	90 to 200	25 to 137	59	
Natural gas				0.25
Fuel oil				0.52
Small boilers (less than 500 hp)	Less than 20			
Natural gas		5 to 92	33	0.14
Fuel oil		15 to 387	122	0.49
Large boilers (500 hp and larger)	20 to 90			
Natural gas		45 to 149	91	0.28
Fuel oil		214 to 282	258	0.62
Power plant steam generators	200 to 2,000			
Natural gas		75 to 320	205	0.36
Fuel oil		275 to 600	420	0.78

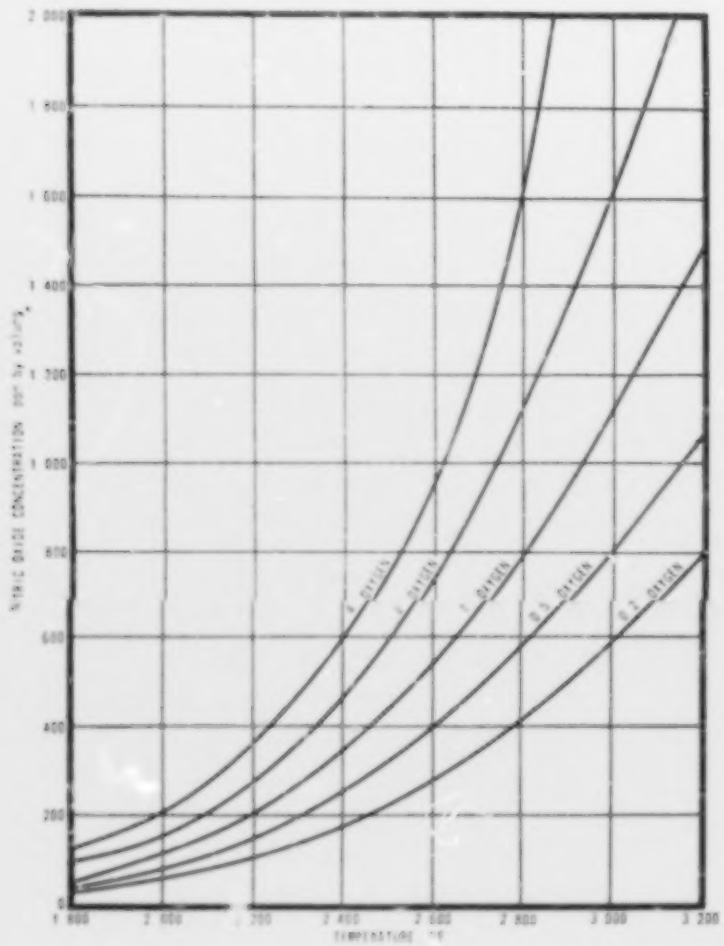


Figure 380. Equilibrium concentrations of nitric oxide in the range 1,800° to 3,200°F as per the reaction: $N_2 + O_2 \rightleftharpoons 2NO$ at 78% N_2 (calculated from data in Hougen and Watson, 1945).

Emission concentrations of oxides of nitrogen from combustion equipment are apparently governed by the formation rate of nitric oxide. Measured NO_x concentrations from large boilers, as shown in Table 145 and Figure 381, are well below equilibrium concentrations at maximum firebox temperatures. For oil-fired steam generators, the exit NO_x concentrations of Table 145 (175 to 600 ppm) correspond to equilibrium at 2,000° to 2,450°F, respectively, and 3 percent oxygen. Theoretical flame temperatures are well in excess of 3,600°F where the equilibrium concentration is 4,150 ppm at 3 percent oxygen. Measuring firebox temperatures or residence times in the hottest zone is not feasible. Nevertheless, the gases can be assumed to be subject to temperatures in excess of 3,000°F in large fireboxes, at least momentarily. On the basis of measured exit concentrations, the residence time at maximum temperature appears to be extremely short.

The rate of formation of NO increases markedly above 3,000°F, as shown in Table 146. Times of formation of 500 ppm nitric oxide were calculated at 3 percent oxygen and 75 percent nitrogen. These calculated values may be somewhat low in that all the nitrogen fixation is assumed to occur at the exit oxygen concentration. Some fixation would probably take place at larger oxygen concentrations before combustion is completed. The times of formation illustrate the rapid change in rate between 2,800° and 3,600°F. At 2,800°F, the time for formation of 500 ppm NO is 16.2 seconds; at 3,200°F, the time is 1.10 seconds; and at 3,600°F, 0.117 second.

At any given temperature, the decomposition ($2NO \rightleftharpoons N_2 + O_2$) rate constant is much greater than the formation rate constant. This fact may lend hope that NO could be decomposed back to the elements before other more stable oxides are formed. This latter possibility appears blocked by the marked slowness, if not stagnation, of the decomposition rate in the necessary temperature range--2,000°F and lower. Decomposition becomes negligible below about 3,200°F, according to Ermenc (1956), and no known data indicate that measurable decomposition occurs below 2,800°F. For the residence times possible in boiler fireboxes, any decomposition taking place below 3,000°F would appear to be insignificant. In any case, measured NO_x emissions are well below the 2,800°F equilibrium concentration of 1,380 ppm. Decomposition cannot occur when NO concentrations are less than equilibrium concentrations.

Since NO formation rate constants are extremely high in the range of 3,500° to 4,000°F, a fraction of a second's residence time more or less can make a significant difference in NO and NO_x concentrations. Measurements of oxides of nitrogen at large steam generators, in fact, bear this out. NO_x concentrations at these sources are extremely variable, indicating that there are small, almost imperceptible changes in operating conditions that greatly increase or decrease NO_x emis-

Table 146. EQUILIBRIUM CONCENTRATIONS AND TIMES OF FORMATION OF NITRIC OXIDE AT ELEVATED TEMPERATURES AT 75 PERCENT NITROGEN AND 3 PERCENT OXYGEN

Temperature, °F	Equilibrium concentration of nitric oxide, ppm[a]	Time of formation of 500 ppm NO, seconds[b]
2,000	180	
2,400	550	1,370
2,800	1,380	16.200
3,200	2,600	1.100
3,600	4,150	0.117

[a]Hougen and Watson, 1945.
[b]Daniels and Gilbert, 1948.

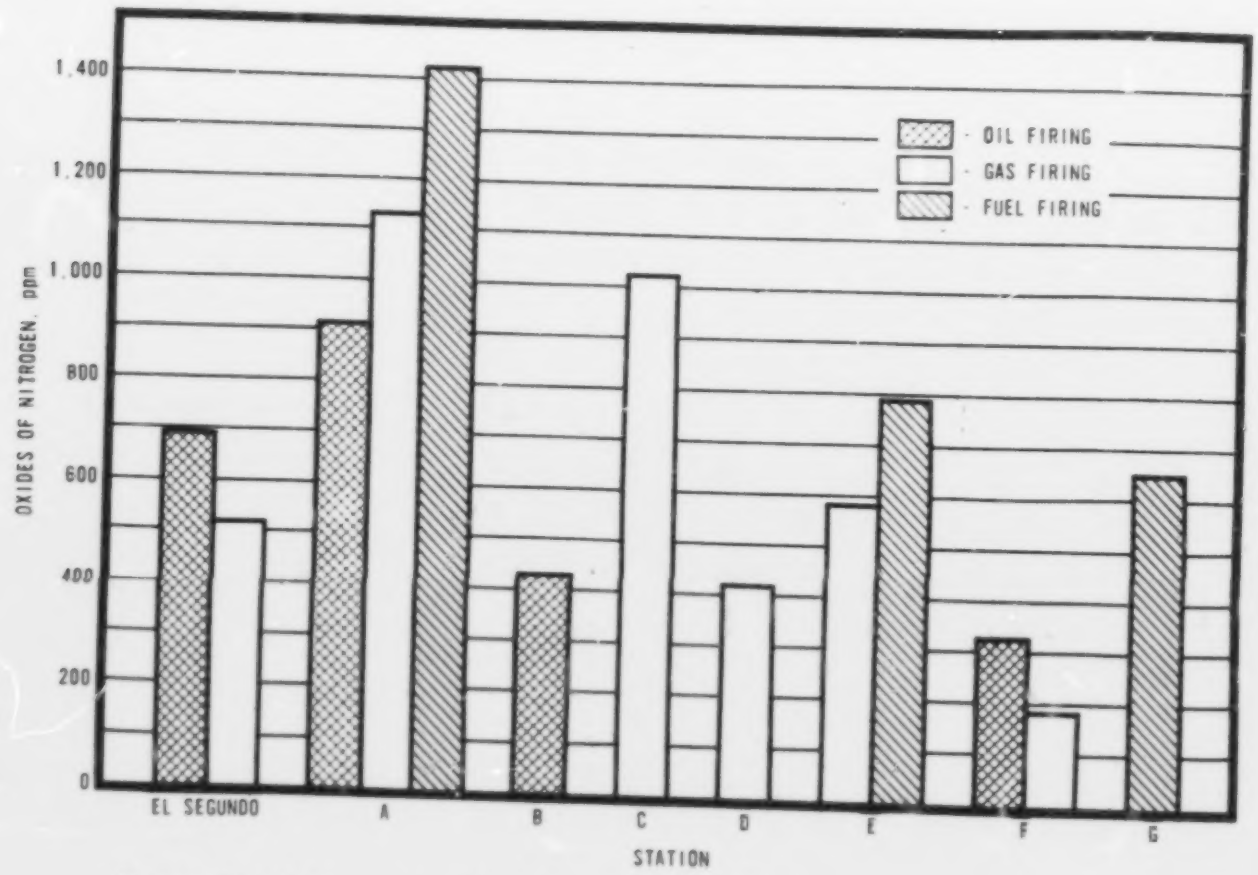


Figure 381. Oxides of nitrogen concentrations in gases from various gas-fired, oil-fired, and coal-fired steam generators (Barnhart and Diehl, 1960).

sions. In studying effects of any specific operating condition on NO_x, great care must be taken to see that other variables are not inadvertently changed in the process.

Emissions of oxides of nitrogen are functions of nitrogen and oxygen concentrations in the firebox. Since there is an abundance of nitrogen in combustion airstreams, oxygen, the reactant in short supply, governs the rate of production of nitric oxide. Thus, at a given firebox temperature, NO formation increases with oxygen concentration. The data in Figure 382 illustrate this point. NO_x concentrations were measured at oxygen concentrations from 1.5 to 3.5 percent from an oil-fired steam generator operating at full load. The listed NO_x concentrations are comparatively small for equipment such as this, but show the effect of reduced oxygen. The figures were extrapolated to smaller and larger oxygen concentrations, principally for purposes of illustration. Note that a reduction from 3.5 to 1.5 percent oxygen produces a definite--approximately 20 percent--reduction in NO_x.

Other tests have been made, both on gas and oil firing, with oxygen concentrations approaching the theoretical combustion requirement. These studies indicate that reductions of greater than 30 percent can probably be effected at reasonable oxygen concentrations, that is, 0.5 percent or slightly higher. As will be discussed later in this chapter, somewhat greater reductions of NO_x can be attained by manipulating the points of entry of combustion air.

As would be expected, fuels producing higher flame temperatures also produce greater NO_x emissions. The data in Table 145 and Figures 381 and 383 show that average NO_x emissions are some 35 to 50 percent higher during oil firing than during gas firing. Theoretical flame temperatures are 200° to 300°F higher on oil firing than on gas firing. Barnhart and Diehl (1960) found that the same phenomenon was true for the burning of coal, also a hotter fuel than oil. They report NO_x concentrations at several different installations burning oil, gas, and coal. The values shown in Figure 381 emphasize the wide variations in NO_x that can be expected from similar equipment. In general, fuels with higher carbon/hydrogen ratios produce higher flame temperatures and greater NO_x concentrations.

Analyses have shown that NO_x emissions vary with firebox and burner designs and with operations that tend to affect maximum temperature, oxygen concentration, and residence time at maximum temperature. Multiple-port burners, in general, are associated with larger NO_x concentrations

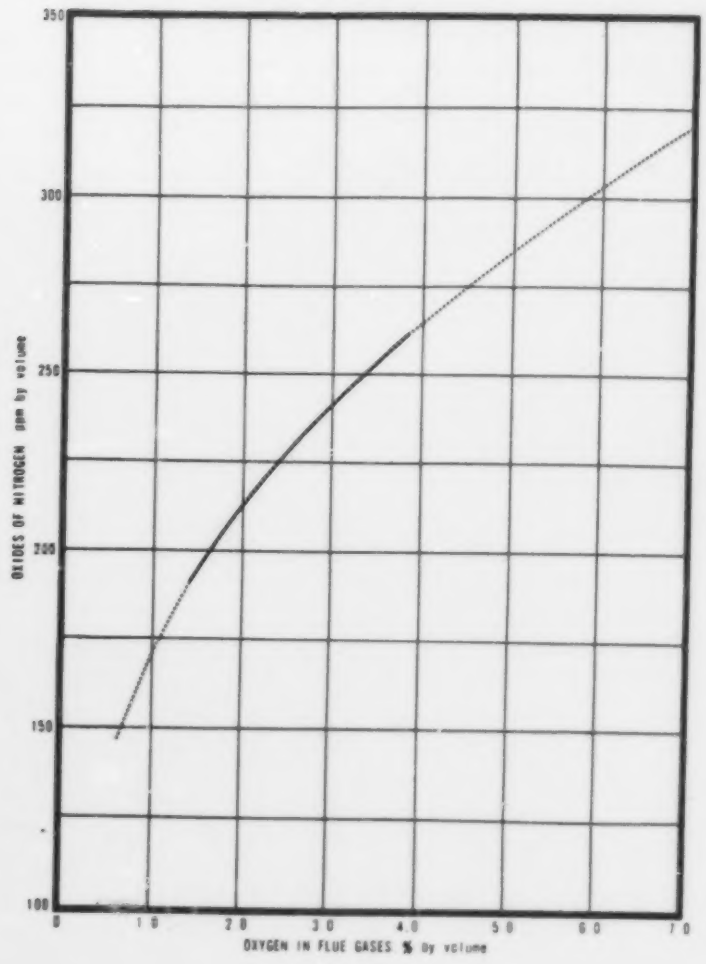


Figure 382. Effect of residual oxygen on NO_x emissions.

than single-port burners are. This is attributed to the greater amount of flame cooling by radiation in the case of single-port burners. With multiple-port burners, a large part of the burning gases is surrounded by the flames from other burners. Thus, the inside burners cannot "see" radiant heat exchange surfaces and cannot, therefore, give up their heat rapidly.

A further indicator of the effect of flame cooling is the reduction in NO_x at reduced firing rates noted by Barnhart and Diehl (1960). On a test furnace at full load, the NO_x concentration was measured as 300 ppm. As the fuel input was reduced to one-half and one-quarter load, NO_x values dropped to 185 and 145 ppm, respectively.

Maximum measured firebox temperature decreased from 3,165°F, to 3,010°F, to 2,110°F. Lowering the burner input apparently allows the flame to be cooled faster as heat is radiated to heat transfer surfaces in the walls of the firebox.

Possibly the greatest contributor to greater nitric oxide formation in large steam generators is the preheating of combustion air. In most instances, combustion air is preheated to about 600°F before introduction into the firebox. As a result, maximum firebox temperatures are 500° to 600°F greater than would be the case if ambient-temperature air were used. There are few good data regarding the effect of temperatures of combustion air on NO_x formation. Barnhart and Diehl (1960) report only a 17 percent NO_x reduction when the combustion air temperature is reduced from 560° to 97°F. Another unpublished source reports a better than 75 percent reduction of NO_x when air preheat is eliminated.

The nitrogen content of the fuel is generally considered to have little effect on NO_x formation. There is so much nitrogen in the combustion gases that fuel nitrogen is relatively inconsequential. Moreover, fuel sulfur does not appear to affect NO_x formation. Sulfur has been injected experimentally into fuel oils. There was no significant difference in NO_x concentrations, even though the sulfur content was increased 4 times.

Estimating NO_x Emissions

Mills et al. (1961) measured NO_x emissions from a wide variety of combustion equipment ranging from small kilns to large steam generators. From these data, they were able to establish a general relationship between gross heat input and NO_x, which is shown in Figure 383. Data cover both gas and oil firing; gross heat inputs range from less than 10,000 Btu per hour (9 scfh natural gas) to 2 million Btu per hour (a 220-megawatt power plant steam generator). The data for both fuels plotted to straight lines on log-log coordinates, even though there are decided differences in firebox design, excess air, and flame temperature over the range of equipment tested. As would be expected, NO_x values are lower (about 50 percent) for gas firing than for oil firing. The carbon/hydrogen ratios of most oils are about twice those of common natural gases, and oil flame temperatures are 200° to 300°F higher.

NO_x emissions from almost any combustion device can be estimated with the curves of Figure 383. For instance, a 200-horsepower oil-fired boiler operating at 80 percent overall efficiency would have a gross heat input of 8,360,000 Btu per hour. From Figure 383, emissions are 1.1 pounds of NO_x per hour.

When combustion air is preheated, preheat must be added to the gross input. For example, a 1,100,000-pound-per-hour steam generator has a rated fuel input of 1.6×10^9 Btu per hour. In addition, combustion air is preheated from 60° to 600°F. The difference in combustion air temperatures represents a 14 percent increase in gross heat input. The adjusted gross input is, therefore, 1.82×10^9 Btu per hour, which, the curve shows, is equivalent to a discharge of 1,030 pounds of NO_x per hour.

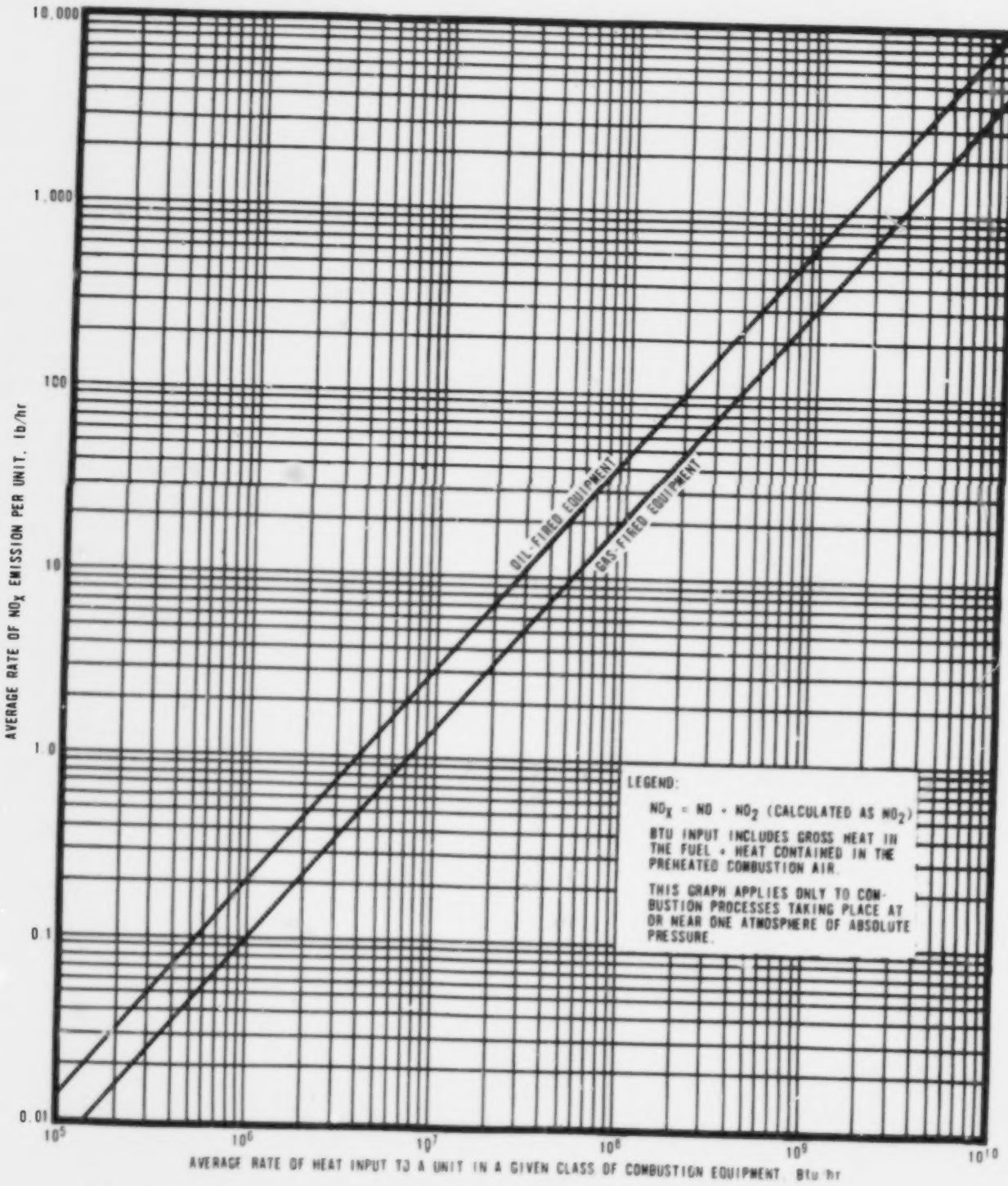

10,000
1,000
100
10
1.0
0.1
0.01
AVERAGE RATE OF NO_X EMISSION PER UNIT, lb/hr
OIL-FIRED EQUIPMENT
GAS FIRED EQUIPMENT
LEGEND:
NO_X = NO + NO_2 (CALCULATED AS NO_2)
BTU INPUT INCLUDES GROSS HEAT IN THE FUEL + HEAT CONTAINED IN THE PREHEATED COMBUSTION AIR.
THIS GRAPH APPLIES ONLY TO COMBUSTION PROCESSES TAKING PLACE AT OR NEAR ONE ATMOSPHERE OF ABSOLUTE PRESSURE.
10^5
10^6
10^7
10^8
10^9
10^{10}
AVERAGE RATE OF HEAT INPUT TO A UNIT IN A GIVEN CLASS OF COMBUSTION EQUIPMENT, Btu/hr

Figure 383. Estimation of average unit NO_X emissions from similar pieces of combustion equipment (Mills et al., 1961).

The gross heat input as used in Figure 383 is an indirect indicator of residence time in the firebox, as well as volume rate of the effluent. The curves represent typical industrial equipment designed neither to decrease nor increase NO_x emissions. For any given piece of equipment, wide deviations may be expected if excess air rates or fuel compositions are changed greatly from normal.

AIR POLLUTION CONTROL EQUIPMENT

A discussion of control equipment serving large gas- or oil-fired boilers and heaters must necessarily be theoretical at present inasmuch as most combustion air contaminants have not been controlled, except on a pilot plant or experimental basis. Except for soot-blowing particulate collec-

tors, few installations of control equipment are serving gas- or oil-fired steam generators.

Air pollution control equipment would necessarily be limited to power plant steam generators or other fired combustion equipment of comparable size. Small and intermediate-size boilers and heaters are not likely to need any control devices unless fuels are highly contaminated. Normally no attempt is made to control even those relatively heavy particulate concentrations emitted from intermediate-size boilers during soot blowing. Where optimum air pollution control is desired in smaller equipment, it is normal practice to burn only clean fuels such as natural gas and low-sulfur distillate oils and to employ high-efficiency burners.

The control of air contaminants from power plant steam generators must be considered from a number of aspects. Some contaminants are amenable to some degree of control through firebox and burner modifications, namely, sulfur trioxide, oxides of nitrogen, and combustible particulates. Others, such as sulfur dioxide and inorganic particulates, can be removed only by treatment of effluent gas. No one control method now under study is capable of removing all types of contaminants emitted to the atmosphere from large combustion sources.

Sulfur Compounds

Four major methods of controlling sulfur dioxide and trioxide are potentially feasible: Scrubbers, cloth filters, dry adsorbers, and electrical precipitators. Scrubbers and possibly adsorbers are the only ones that could be used without auxiliary control mechanisms. With both cloth filters and precipitators, converting the sulfur dioxide to a collectible particulate form would first be necessary. This would necessitate either oxidation to sulfur trioxide and sulfuric acid, or reaction with an alkaline additive.

Conceivably the problem could be attacked from the standpoint of sulfur trioxide elimination only. The trioxide is more objectionable than the dioxide because it is highly acidic and imparts visible opacity to flue gases. Nevertheless, in most areas, sulfur trioxide collection would be only an intermediate step in that it would remove no more than 5 percent of the total sulfur oxides emitted from a given combustion source. Emissions of sulfur trioxide could be prevented by (1) inhibiting trioxide formation, (2) neutralizing with dry alkaline additives, or (3) selectively controlling the effluent.

Combustible Particulates

As explained in the second part of this chapter, combustible particulates are not common in exit gases from small and medium-size combustion equipment except during startup periods. Generally, combustibles almost always result from poor maintenance or operation, or improper selection of burner or fuel. In large boilers, fuel usage and combustion air are carefully monitored to provide nearly perfect combustion. Combustible contaminants are seldom emitted in concentrations sufficient to impart perceptible opacity or blackness to stack gases. Conceivably, combustibles could be incinerated in an afterburner. An installation such as this would, however, be highly unlikely and might occur only where the fuel burned is essentially a waste product. Examples might be wood pulp or petroleum products contaminated with inorganic sludge.

Soot Collectors

The only air pollution control devices that have found ready acceptance on oil-fired power plant boilers are dust collectors used to control particulates during soot blowing. This equipment serves principally to collect large particulate matter--greater than 10 microns--that would otherwise settle in the immediate area. Soot collectors are used only during periods of soot blowing. They are not designed to control the extremely fine particulates emitted during normal oil firing, particularly the submicron particulates responsible for opaque plumes.

Dry, small-diameter, multiple cyclones are the most common soot control devices installed. This equipment is reasonably inexpensive, and pressure drops do not usually exceed 4 inches of water column. Nevertheless, any dry or wet collector capable of 90 percent or greater collection above 10 microns would be satisfactory in many locales. More efficient controls, such as cloth filters may need to be installed to collect soot-blown air contaminants where fallout is causing a public nuisance.

No good data are available regarding the soot collection afforded by centrifugal collectors on large steam generators. This is due principally to the difficulty of obtaining representative test samples during soot blowing. As can be appreciated, dust loadings during tube-lancing operations are extremely variable. When a given section of tubes is lanced, the resultant dust concentration is heaviest when steam or air is first injected through the lance. Inasmuch as the efficiency of particulate collection cannot be measured accurately, the common yardstick for acceptability of a soot collector is its observed ability to prevent fallout of large particulates in downwind areas.

The soot collectors normally encountered at steam generators are not designed to collect the submicron particles emitted during normal firing. It is

doubtful that operators of large oil-fired boilers would install more efficient particulate collection devices unless they also served to remove sulfur or nitrogen oxides. Most devices that show promise of SO_2 removal would also, however, collect solid particulate matter. Scrubbers, cloth filters, and precipitators--all possible controls of sulfur oxides--would remove a major portion of the particulate matter emitted from oil-fired combustion equipment.

Sulfur Oxides Collection

The removal of sulfur oxides has been the subject of considerable investigation, more often in connection with metal-smelting and coal-firing operations than with oil-fired steam generators. In a few installations, these oxides are being collected from coal- and oil-fired combustion gases. Several control methods show definite promise, but to date, none are sufficiently inexpensive to warrant widespread installation.

Scrubbers for Sulfur Oxides

The only full-scale sulfur oxide controls installed at steam power plants have been scrubbers using water or basic aqueous solutions. The few installations of this sort existing today are in England. They can provide 90 percent and greater removal of both sulfur dioxide and sulfur trioxide. Three principal scrubbing methods (Bienstock et al., 1958) using water solutions have been studied for power plant use: The nonregenerative limestone process, the Fulham-Simon-Carves process, and the regenerative sodium sulfite process. They differ mainly in costs, scrubbing vehicles, by-products, and quantities of wastes produced. In no case are the by-products of sufficient value to offset fully the costs of installing and operating the scrubber.

In the nonregenerative limestone process shown in Figure 384, a slurry of 5 to 10 percent calcium carbonate is circulated through a packed tower. Removal of about 90 percent of the sulfur produces calcium sulfite and calcium sulfate. Slurry from the tower is crystallized, settled, and mixed with more limestone before it is recirculated to the scrubber. Calcium hydroxide is more reactive than the carbonate, but the added cost makes it unattractive. The calcium sulfite-sulfate sludge produced in the process has no by-product value and presents a waste disposal problem. If disposal as sulfite is not feasible, the sulfite is oxidized to sulfate.

The Fulham-Simon-Carves process employs an ammoniacal liquor to remove sulfur oxides, also in a packed tower. Ammonium sulfate fertilizer and sulfur are by-products. Ammonia reacts with sulfur oxides to form ammonium sulfate

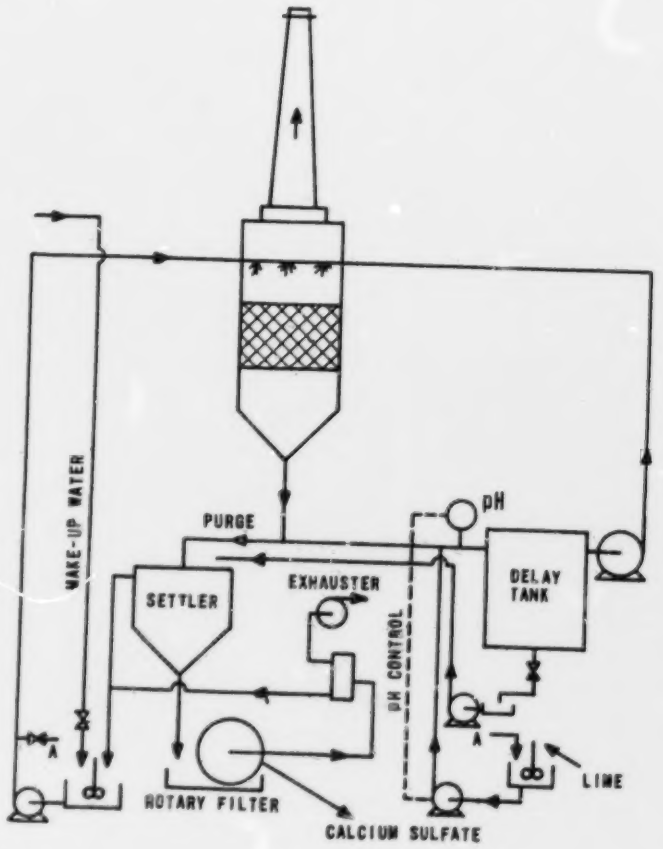


Figure 384. The nonregenerative limestone process for the scrubbing of sulfur oxides (Rees, 1955).

principally, with smaller amounts of sulfite, bisulfite, and thiosulfate. After treatment with sulfuric acid, the spent scrubber liquor is autoclaved at 200 psig and 360°F to produce sulfur and ammonium sulfate. The system is described in the flow diagram of Figure 385.

The regenerative sodium sulfite process of Figure 386 uses a scrubbing solution of sodium sulfite and sodium bisulfite. Sulfur dioxide reacts with sodium sulfite to form sodium bisulfite in the scrubber as follows:

$$H_2O + SO_2 + Na_2SO_3 \rightleftharpoons 2\,NaHSO_3.$$

The spent scrubber solution is desulfated and treated with zinc oxide, which converts the bisulfite back to sulfite and precipitates zinc sulfite. Zinc sulfite is calcined, driving off sulfur dioxide and regenerating zinc oxide. Sulfur dioxide is a by-product of the sodium sulfite process. The principal waste is a sludge of calcium sulfate.

In any scrubbing process, combustion gases are cooled to the point where they are no longer markedly buoyant. Auxiliary blowers must be employed to direct the gases through stacks. Even with additional blowers, the scrubbed gases could settle to ground level in immediately adjacent areas be-

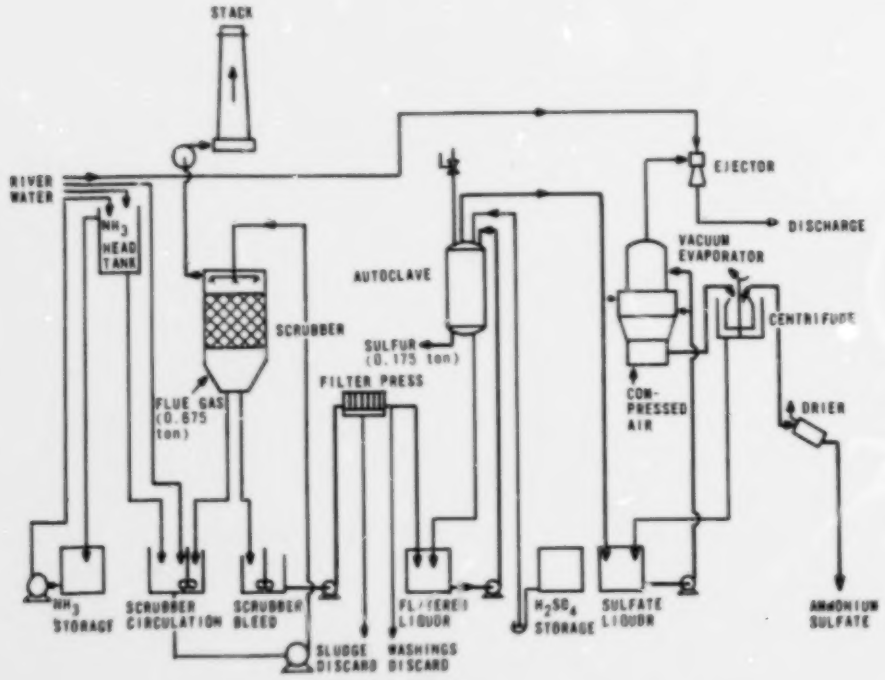


Figure 385. The Fulham-Simon-Carves ammoniacal liquor process for the scrubbing of sulfur oxides (Rees, 1955).

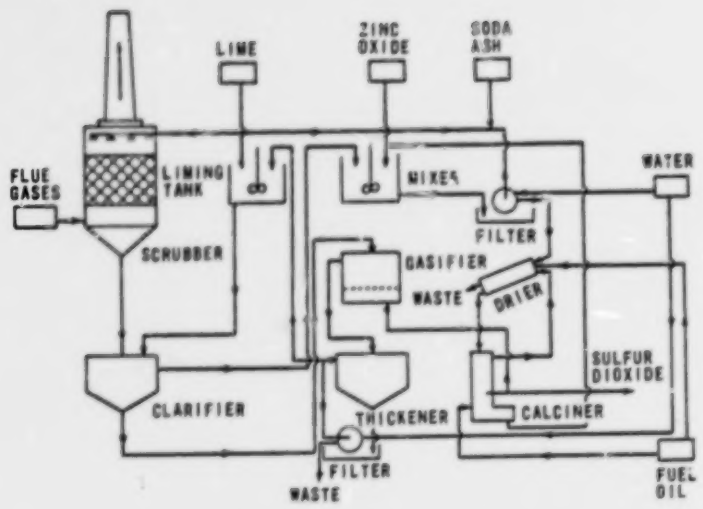


Figure 386. The regenerative sodium sulfite process for scrubbing sulfur oxides (Rees, 1955).

fore residual sulfur dioxide could be sufficiently diluted. Localized sulfur dioxide buildups have in fact occurred at a power station in England where scrubbing is employed.

Scrubbing by any of the described methods requires an appreciable investment in equipment and materially increases operating costs at a steam power plant. Field et al. (1957), made an extensive comparative-cost study of the three processes using as a base a coal-fired steam generator exhausting 330,000 scfm combustion gases. A high-sulfur coal and a low-sulfur coal were considered. Their findings are summarized in Table 147 along with a similar comparison based upon oil burning. The heat input to an oil-fired steam generator producing the same volume and sulfur oxide concentration would be slightly higher than that of the coal-fired unit. Burning 60 tons of coal per hour would produce about the same volume of gases as burning 283 barrels of U.S. Grade No. 6 fuel oil per hour.

It can be seen from Table 147 that 90 percent removal by alkaline scrubbing represents an initial investment of $1,646,750 to $4,945,400, depending upon the process and sulfur content of the fuel. When fuel oil of about 1.6 percent is burned, the limestone process, with no by-products, is seen to be the least expensive of the three to install and operate, even if credit is allowed for by-products. At greater sulfur contents, both the ammonia and sulfite processes become comparatively more attractive by reason of increased by-product value. At fuel sulfur concentrations of 5 percent and greater, the lower operating costs of the ammonia and sulfite processes are somewhat offset by the greater initial investment required in comparison with the limestone process. Under existing economics, most operators consider scrubbing costs prohibitive. Operating expenses alone range from 10 to 25 percent of fuel costs on oil firing and are comparatively higher for coal burning.

Table 147. COSTS OF SCRUBBING SO_x FROM 20 MILLION SCFM FLUE GASES AT COAL-FIRED[a] AND OIL-FIRED[b] POWER PLANTS (Calculated from data in Field et al., 1957)

	0.083% SO_x by volume		0.30% SO_x by volume	
Total investment[c]				
Limestone process	$1,646,750		$1,922,200	
Ammonia process	3,221,100		4,945,400	
Sulfite process	2,433,000		3,105,800	
Annual operating costs[d]				
$/ton coal burned	No credit for products	Credit for products	No credit for products	Credit for products
Limestone process	1.24	---	1.93	---
Ammonia process	2.99	1.62	6.54	1.43
Sulfite process	2.10	1.97	3.21	2.17
$/bbl of oil burned				
Limestone process	0.263	---	0.409	---
Ammonia process[f]	0.643	0.343	1.380	0.303
Sulfite process	0.445	0.418	0.704	0.460

[a]At 60 tons/hr coal burned, sulfur content 1.5 and 5.0%, respectively.
[b]At 283 barrels/hr No. 6 fuel, sulfur content 1.6 and 5.5%, respectively.
[c]Includes working capital at 10% on fired capital.
[d]No provision for interest or return on investment.
[e]Ammonium sulfate at $32/ton, sulfur at $28/ton, SO_2 at $14/ton.
[f]Anhydrous ammonia at $100/ton delivered.

In this analysis no consideration was made for waste disposal. If sludge from the processes could not be dumped into existing facilities, disposal costs could be appreciable. Far greater quantities of sludge are produced in the limestone process than in either of the other two methods. In the sulfite form, limestone process sludge represents a greater hazard to marine plant and animal life than calcium sulfate does. Even calcium sulfate is undesirable inasmuch as it settles at the point of discharge, and continuous operation results in a significant buildup in ponds, streams, and so forth.

Baghouses and Precipitators

No particulate-matter collector by itself is a satisfactory control for all sulfur oxides from oil-fired power plants. This includes centrifugal collectors as well as baghouses and electrical precipitators. At best these devices can be expected to remove only sulfur trioxide. Sulfur dioxide is a gas at temperatures well below normal stack conditions and is unaffected by these collectors. Nevertheless, attempts have been made to use baghouses and precipitators principally to minimize acid fallout damage and visible emissions. Even for these limited purposes, the particulate collectors have not been completely successful.

Cloth filters are effective only as long as the fabric remains reasonably clean and permeable. Experiments at oil-fired steam generators have shown that the collected materials adhere to fabrics and tend to hydrate upon cooling. The resulting crust-like formations are almost impossible to remove and render the cloth impermeable to airflow. Moreover, many fabrics are not resistant to acids and rapidly disintegrate with use.

Several pilot plant studies have been made covering the feasibility of single-stage precipitators for controlling visible emissions. In one instance, a full-size electrical precipitator was installed to control the 350,000 scfm discharged from an oil-fired 1,200,000-pound-per-hour power plant steam generator. The precipitator was on the downstream side of the air heater where temperatures ranged from 280° to 350°F. At these temperatures, much of the sulfur trioxide was in the gaseous state and passed through the precipitator. A pilot precipitator showed considerably better SO_3 removal and no visible plume when gases were cooled to about 90°F, well below the water dew point (based upon moisture content only). Operation at less than 200°F stack temperatures is not considered practical by power plant operators because of resultant corrosion and condensation.

The one full-scale electrical precipitator was not consistently effective in controlling plume opacity below 40 percent during oil firing. Data covering its operation are included in Table 148. During part of the test period, dolomite or ammonia additives were injected into the combustion gases ahead of the precipitator. Table 148 shows that, with no additives, efficiencies of SO_3 and particulate matter removal were less than 50 percent during most trials. Most of the particulate concentrations shown in Table 148 are abnormally high for an oil-fired steam generator and indicate a large percentage of combustible particulates. Normal particulate concentrations are between 0.02 and 0.04 grain per scf. The 87 to 90 percent maximum efficiencies were achieved at loadings of approximately 0.3 grain per scf. The 26 to 46 percent particulate removal of Runs 3, 4, 6, and 7 are probably more indicative of expected precipitator performance than the highest efficiencies are. The reported particulates removal of 0.04 grain per scf corresponds to about 110 pounds of precipitator catch per hour. Moreover, the 10 to 20 ppm concentrations of SO_3 in precipitator discharge gases were appreciable. Under optimum conditions, the opacity of full-scale precipitator exhaust gases was about 20 percent when oil of 1.6 percent sulfur was burned. When the precipitator was turned off, the plume was of approximately 60 percent opacity.

Alkaline Additives to Neutralize Sulfur Trioxide

Inexpensive alkaline materials have been injected into flue gases to neutralize sulfur trioxide and sulfuric acid. The purposes are to inhibit corrosion of boiler tube surfaces and prevent visible emissions as well as acid fallout damage. The most common materials used for selective SO_3 neutralization are calcium and magnesium oxides, hydroxides, and carbonates (dolomite). Some attention has also been directed to the injection of gaseous ammonia.

The purpose of injecting calcium and magnesium compounds is to form neutral sulfates, which are markedly less corrosive and less hygroscopic than sulfuric acid and contribute little to visible opacity. These materials have been mixed with oil fuels and have been injected at fireboxes and various downstream points. The hydroxide is probably the most reactive form. When, however, hydroxides or carbonates are injected into extremely hot areas such as the firebox, they are probably converted to the oxide form before reacting with sulfur trioxide.

Some operators report mild success with these additives in controlling tube corrosion, but their effect on sulfur trioxide concentrations and visible plume formation is questionable. Injection of any calcium or magnesium additive by itself apparently cannot be expected to lower SO_3 in stack gases appreciably. This is indicated by data in Table 148, which show that the reduction in sulfur trioxide concentration across the precipitator is almost the same with and without dolomite. Some operators have reported a mild reduction in visible emissions, but there are few quantitative data on the subject.

The stoichiometric equivalent of 30 ppm by volume SO_3 is 0.055 grain per scf as calcium carbonate, $Ca\,CO_3$. The additive would not usually be injected in concentrations greater than 3 times the stoichiometric equivalent, that is, 0.165 grain per scf as $Ca\,CO_3$. Particles of additive or calcium, or both, or magnesium sulfate do not in themselves appreciably affect plume opacity when

Table 148. EFFICIENCIES OF SULFUR TRIOXIDE AND PARTICULATE REMOVAL BY A FULL-SCALE ELECTRICAL PRECIPITATOR SERVING AN OIL-FIRED STEAM GENERATOR

Run No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Fuel oil rate, 1,000 lb/hr	-	89	89	89	88	88	86	86	86	87	87	87	87	87	87
Temperature, °F	-	295	292	308	308	-	303	309	309	305	309	310	-	318	-
Additive, dolomite, lb/hr	-	-	-	-	-	-	-			90	180	270	-	270	270
ammonia, ppm	-	-	-	-	-	-	-						40		
Particulates, in, gr/scf	-	0.1745	0.0511	0.0609	-	0.0818	0.0650	0.0928	-	0.0947	0.1587	0.0554	0.3378	0.1814	0.2964
out, gr/scf	-	0.1119	0.0382	0.0327	-	0.0463	0.0451	0.0586	-	0.0658	0.0381	0.0226	0.0322	0.1585	0.0386
efficiency, %	-	36	26	46	-	43	30	36	-	22	76	59	90	13	87
SO_2, in, ppm	870	935	832	802	802	808	817	858	817	786	777	767	758	725	781
out, ppm	873	957	860	891	843	833	843	787	834	715	809	821	781	908	814
SO_3 in, ppm	25.8	23.2	21.3	22.5	25.7	22.8	27.4	27.3	28.0	27.5	30.2	30.7	-	25.8	40.5
out, ppm	13.4	16.4	12.6	16.7	15.5	13.2	13.9	13.5	11.9	13.0	10.8	13.2	11.7	10.0	15.2
efficiency, %	48	29	41	26	40	42	49	51	58	53	64	57	-	61	62
Dew point, outlet, °F	-	-	-	-	-	285		-	-	120	120	120	-	120	-

additive particles are appreciably larger than 1 micron. The dolomite powders used for this purpose do not normally contain any appreciable percentage of material smaller than 10 microns.

Gaseous ammonia reacts more readily with SO_3 than dolomite does but is not a great improvement in terms of air pollution. When injected in proper concentrations, ammonia is reported by Rendle and Wilsdon (1956) to decrease plume opacity and SO_3 presumably by the formation of ammonium sulfate. As greater quantities of NH_3 are added, it begins to react with SO_2, forming sulfites and bisulfites, which increase rather than lessen opacity. These latter materials apparently sublime in the range of normal stack temperatures to form extremely small particles. The precise control of ammonia concentrations necessary for plume reduction is not considered practical for most power plant operations.

The mere addition of ammonia, dolomite, or any other additive does not remove air contaminants from a gas stream but converts undesirable sulfur trioxide and sulfuric acid to a less noxious form. The addition of any additive to fuel gases without subsequent control increases particulate emissions.

As will be noted later in this chapter, stack gas additives offer some promise when used in conjunction with cloth filters. This arrangement allows better contact of additives with stack gases and also eliminates the problem of increased particulates.

Other Metal Oxides for Sulfur Dioxide Removal

The use of ammonia, calcium, and magnesium solids has generally been considered only for SO_3 control and only on a throwaway basis, that is, the resultant sulfates would either be allowed to discharge from the stack or would be thrown away if collection devices were used. Bienstock and Field (1960) investigated the use of several more costly metal oxides for the removal of sulfur dioxide in flue gases. These investigations were experimental and used materials considerably more expensive than limestone. Most of the additives could not be used on a throwaway basis. The test materials reacted with sulfur dioxide to form stable compounds, principally sulfides and sulfates. Any usable process for sulfur control in a power plant would require that these materials be regenerated for continuous use. This would normally necessitate electrolytic or thermal decomposition, usually with the production of sulfur dioxide as a by-product.

The adsorptive or reactive capacities of several metal oxides are included in Tables 149 and 150 for the two temperatures of 265° and 625°F, respectively. Note that manganese oxides and copper oxides are among those having the greatest adsorptive capacities. Note also that calcium and magnesium compounds have relatively low capacities for sulfur dioxide in comparison with the other materials tested.

If metal oxide adsorption were to be employed at a power plant, it would probably necessitate a floating bed absorber with special consideration taken to minimize the pressure drop across the unit. In the bench-scale experiments of Bienstock and Field, a fixed-bed arrangement was used. A design such as this would probably result in excessive pressure drops in a steam power plant and would also require a significant amount of extra labor.

Baghouses With Dolomite Addition for Sulfur Trioxide Removal

The principal objection to baghouse operation, that is, encrustation, blinding, and deterioration of the cloth, can be overcome by injecting dry dolomite dust into the gas stream ahead of the collection device. Before startup, the bag filters are precoated with dolomite. During operations, the additive is continuously injected into the gas stream at 2 or 3 times the stoichiometric equivalent of the sulfur trioxide content. Sulfur trioxide reacts in the gas stream and on the surface of the bags to form calcium sulfate, a collectible solid.

The data in Table 151 were taken from a pilot installation used to control gases from an oil-fired steam generator. The gases were cooled in a surface heat exchanger from the normal stack temperature (290° to 305°F) to less than 185°F. Dry powdered dolomite was added just ahead of the centrifugal fan preceding the baghouse. The dolomite addition rate was approximately 0.1 grain per scf, about 3 times the stoichiometric SO_3 equivalent at 20 ppm. Pressure drops across the unit ranged from 2 to 3 inches water column. Table 151 shows that the baghouse effected an SO_3 removal of greater than 90 percent in most instances, as well as reduction of 100° to 150°F in dew point. The resulting dew points, that is, 110° to 120°F, were close to the water dew points of the gases. No visible emissions were reported from the unit even though the gases were discharged at 165° to 185°F.

This method can be used only to remove sulfur trioxide and particulate matter and prevent visible emissions. It has essentially no effect on the less reactive gas, sulfur dioxide. It provides considerably greater contact between sulfur trioxide and dolomite than is afforded by additive injection without the baghouse. The method shows promise primarily in that it could

Table 149. EFFECTIVENESS OF VARIOUS COMPOUNDS IN ADSORBING 90% OF 3,000 ppm OF SULFUR DIOXIDE FROM GASES AT 265°F[a, b] (Bienstock and Field, 1960)

Adsorbent	Crystalline phase (X-ray analysis)		Purity, wt %	Bulk density, g/Co	SO_2 adsorbed, g/100 g adsorbent	Preparation
Manganese oxide	$MnO_{1.88}$		90	0.14	33	$MnSO_4 \xrightarrow[NH_3]{(NH_4)_2S_2O_8}$ Ppt washed and dried at 130°C
Cobalt oxide	Co_3O_4		97	0.46	25	$CoSO_4 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Manganese oxide	$MnO_{1.88}$			0.50	23	$MnSO_4 \xrightarrow{\text{Electrolysis}}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Manganese oxide	γ-Mn_2O_3		96	0.67	19	$MnSO_4 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Aluminum-sodium oxide		Al_2O_3 Na_2O	73 25	0.54	18	$Al_2(SO_4)_3 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated with H_2 at 600 to 640°C for 20 hr
Hopcalite		CuO MnO_2	11 79	0.93	13	Dried at 130°C
Cobalt oxide	Co_3O_4		100	0.66	12	$CoSO_4 \xrightarrow[NaOH]{NaOCl}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Chromium-sodium oxides		Cr_2O_3 Na_2O	70 26	0.91	12	$Cr_2(SO_4)_3 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated with H_2 at 600 to 640°C for 20 hr
Nickel oxide	NiO		91	0.74	9	$NiSO_4 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Aluminum-potassium oxides	γ-Al_2O_3	Al_2O_3 K_2O	73 21	0.61	6	$Al_2(SO_4)_3 \xrightarrow{K_2CO_3}$ Ppt washed, dried at 130°C, and heated with H_2 at 600 to 640°C for 20 hr
Nickel oxide	NiO		90	1.49	6	$NiSO_4 \xrightarrow[NaOH]{NaOCl}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Sodium carbonate	Na_2CO_3		99	0.98	5	Solution of sodium carbonate dried at 130°C and heated in vacuo at 300 to 340°C for 20 hr
Sodium stannate			95	0.91	4	Sodium stannate, dried at 130°C and heated in vacuo at 300 to 340°C for 20 hr
Iron oxide	α-Fe_2O_3		93	0.98	3	$Fe(NO_3)_3 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated at 300 to 340°C in a stream of nitrogen for 3 hr
Sodium aluminate	$NaAlO_2$		96	0.90	3	Solution of sodium aluminate, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Cadmium oxide	CdO		97	1.13	1	$CdSO_4 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated in vacuo at 370 to 400°C for 20 hr
Copper oxide	CuO		99	0.89	1	$CuSO_4 \xrightarrow{Na_2CO_3}$ Ppt washed, compressed at 4,000 psi, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Potassium carbonate			98	0.89	1	Solution of potassium carbonate dried at 130°C and heated in vacuo at 300 to 340°C for 20 hr

Bismuth oxide (αBi_2O_3), molybdenum oxide (MoO_3), lead oxide (PbO), zinc oxide (ZnO), and calcium hydroxide ($Ca(OH)_2$) adsorbed less than 1 g of sulfur dioxide for 100 g of charge.

[a] The 265°F is close to the stack discharge temperature of power plant steam generators.
[b] Hourly space velocity of gas, 1,050 hr^{-1}; mesh size of adsorbent, 8-24.

Table 150. EFFECTIVENESS OF VARIOUS COMPOUNDS IN ADSORBING 90% OF 3,000 ppm OF SULFUR DIOXIDE FROM GASES AT 625°F[a,b] (Bienstock and Field, 1960)

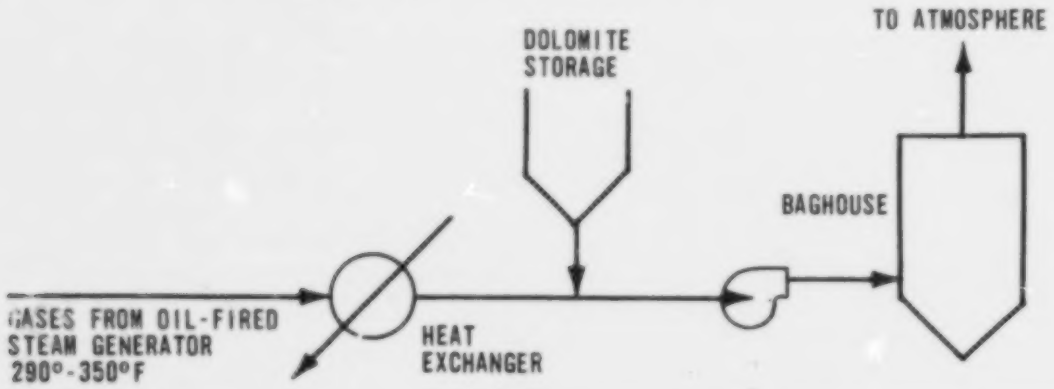
Adsorbent	Crystalline phase (X-ray analysis)		Purity, wt %	Bulk density, g/Co	SO_2 adsorbed, g/100 g adsorbent	Preparation
Manganese oxide	$MnO_{1.98}$		94	0.14	64	$MnSO_4 \xrightarrow[NH_3]{(NH_4)_2S_2O_8}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Manganese oxide	γ-Mn_2O_3		96	0.67	58	$MnSO_4 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Hopcalite		MnO_2	79	0.92	57	
Copper oxide	CuO	CuO	11			Dried in vacuo at 300 to 340°C
			99	0.89	56	$CuSO_4 \xrightarrow{Na_2CO_3}$ Ppt washed, compressed at 4,000 psi, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Manganese oxide	$MnO_{1.88}$			0.50	55	$MnSO_4 \xrightarrow{Electrolysis}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Cobalt oxide	Co_3O_4		97	0.46	47	$CoSO_4 \longrightarrow$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Cobalt oxide	Co_3O_4		100	0.66	44	$CoSO_4 \xrightarrow[NaOH]{NaOCl}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Lead oxide	PbO		99	1.25	18	$Pb(NO_3)_2 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Aluminum-sodium oxides	Al_2O_3	Na_2O	73 25	0.54	17	$Al_2(SO_4)_3 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated with H_2 at 600 to 640°C for 20 hr
Chromium-sodium oxides		Cr_2O_3 Na_2O	70 26	0.91	16	$Cr_2(SO_4)_3 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated with H_2 at 600 to 640°C for 20 hr
Sodium aluminate	$NaAlO_2$		96	0.90	10	Solution of sodium aluminate, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Nickel oxide	NiO		91	0.74	9	$NiSO_4 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Nickel oxide	NiO		90	1.49	7	$NiSO_4 \xrightarrow[NaOH]{NaOCl}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr
Aluminum-potassium oxides	γ-Al_2O_3	Al_2O_3 K_2O	73 21	0.61	6	$Al_2(SO_4)_3 \xrightarrow{K_2CO_3}$ Ppt washed, dried at 130°C, and heated with H_2 at 600 to 640°C for 20 hr
Cadmium oxide	CdO		97	1.13	5	$CdSO_4 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated in vacuo at 370 to 400°C for 20 hr
Sodium stannate			95	0.91	5	Sodium stannate dried at 130°C and heated in vacuo at 300 to 340°C for 20 hr
Sodium carbonate	Na_2CO_3		99	0.98	4	Solution of sodium carbonate dried at 130°C and heated in vacuo at 300 to 340°C for 20 hr
Iron oxide	α-Fe_2O_3		93	0.98	3	$Fe(NO_3)_3 \xrightarrow{Na_2CO_3}$ Ppt washed, dried at 130°C, and heated at 300 to 340°C in a stream of nitrogen for 3 hr
Calcium hydroxide	$Ca(OH)_2$	$Ca(OH)_2$ CaO	81 19	0.36	2	$Ca(NO_3)_2 \xrightarrow{NaOH}$ Ppt washed, dried at 130°C, and heated in vacuo at 300 to 340°C for 20 hr

Aluminum oxide (γAl_2O_3), bismuth oxide (αBi_2O_3), calcium oxide (CaO), magnesium oxide (MgO) molybdenum oxide (MoO_3), zinc oxide (ZnO), and potassium carbonate (K_2CO_3) adsorbed less than 1 g of sulfur dioxide for 100 g of charge.

[a] The 625°F is the approximate temperature of flue gases at the inlet of the air preheater.

[b] Hourly space velocity of gas, 1,050 hr^{-1}; mesh size of adsorbent, 8-24.

Table 151. FILTERING SO_3 AND DOLOMITE[a] ADDITIVE IN A PILOT BAGHOUSE



Baghouse		In		Out	
Temp, °F	Δ P, in. WC	SO_3, ppm by vol	Dew point, °F[b]	SO_3, ppm by vol	Dew point, °F[b]
185	2	15	250	3.1	150
186	2.2	12.6	230	2.7	120
185	2.2	19.4	260	1.1	120
173	2	12.5	220	0.9	120
165	2	20.4	230	0.6	120
175	3	10.5	250	1.5	110
183	3	16.4	250	1.3	120

[a]Dolomite added at about 3 times stoichiometric SO_3 equivalent at 20 ppm SO_3. Bags precoated with dolomite before startup.
[b]Apparent dew point. True dew point about 115°F.

be used for total sulfur oxides collection if all oxides could be converted to the trioxide form. That an operator would install this control equipment merely to remove the 5 percent or less of the total sulfur represented by SO_3 is doubtful. To be completely successful as a sulfur oxides control, the baghouse process would necessarily require a companion process in which sulfur dioxide would be oxidized to sulfur trioxide presumably with the aid of a catalyst. Catalytic oxidation of sulfur dioxide has not yet been proved economical for oil-fired combustion gases. The point will be discussed later in this chapter.

If more reactive alkaline additives were used rather than dolomite, a substantial SO_2 removal might be afforded. A number of possible materials are listed in Tables 149 and 150; however, most of these are considerably more expensive than dolomite.

Some trials have been made with ammonia additives in conjunction with a pilot baghouse. The resultant ammonium compounds tended to blind the filter cloth, causing excessive pressure drops. The collected material could not be removed from the cloth by normal shaking methods.

Electrical Precipitators With Additives

The use of dolomite with electrical precipitators is not as effective as it is with baghouses. This is probably true for other alkaline materials as well. A baghouse apparently provides the more intimate contact required to push the reaction of basic additives with small concentrations of sulfur trioxide. For effective SO_3 removal in a precipitator, the additive would have to be markedly more reactive than dolomite. Moreover, the resultant neutralized compound would necessarily have to be a particulate collectible in the precipitator.

Carbon Adsorption of Sulfur Oxides

Activated carbon is known to adsorb both sulfur oxides and oxides of nitrogen. Haagen-Smit (1958) measured the quantity of sulfur dioxide adsorbed on various grades of high-quality activated carbon between 77° and 300°F. The data included in Table 152 indicate that a process such as this might not be attractive unless a suitably rapid means of regenerating the carbon were developed. About 13 parts of sulfur dioxide by weight are adsorbed per hundred parts of the best carbons at 150°F. To be practical for a

Table 152. ADSORPTION OF SULFUR DIOXIDE ON ACTIVATED CHARCOAL (Haagen-Smit, 1958)

Charcoal[a]	Adsorption temperature, °F	Flow rate, cfm	Quantity of SO_2, mg SO_2/g charcoal
A	77	0.1	153
	300	0.1	19
B	77	0.1	285
B	150	0.1	127
	300	0.1	29
C	77	0.1	54
	300	0.1	30
D	77	0.1	244
	150	0.1	82
	220	0.1	62
E	77	0.1	143
F	77	0.1	253
G	77	0.1	225

[a]A, B, C, and so on are code letters for the different charcoals tested.

large volume of flue gases, a process such as this would probably require a floating bed with continuous carbon reactivation. In view of the relatively high cost of these carbons, losses on reactivation would have to be minimal to make the process attractive economically.

A German process has been developed by Reinluft that uses a low-grade activated carbon to adsorb both sulfur dioxide and trioxide as well as NO_x. The process is reported to provide 85 percent or better removal of both oxides of nitrogen and sulfur oxides. Sulfur trioxide is first removed at 600° to 800°F. The gases are then cooled to 200°F where sulfur dioxide and oxides of nitrogen are adsorbed. SO_2 and NO are catalytically oxidized to SO_3 and NO_2 on the surface of the carbon. Upon picking up further moisture, the anhydrides are converted to sulfuric and nitric acids.

Oxidation of Sulfur Dioxide

Considerable attention has been given to the oxidation of sulfur dioxide to the trioxide. There are workable processes by which SO_3 could be removed from stack gases; however, most operators would not consider it practical to operate this control equipment unless it would remove essentially all sulfur compounds. The oxidation process is thus a major stumbling point in power plant air pollution control.

As noted earlier, sulfur oxidizes in two steps, the first forming the dioxide, the second, the trioxide. In the manufacture of sulfuric acid, approximately 97 percent conversion to SO_3 is achieved with the use of oxidation catalysts at carefully controlled temperatures. The optimum temperature range for SO_3 formation is between 800° and 840°F. Maximum conversion is accomplished at these temperatures with the aid of vanadium, nickel, and platinum catalysts. Equilibrium at lower temperatures definitely favors the higher oxide, SO_3. This is generally offset by decreased reaction rates.

Attempts have been made to adapt the catalytic process to power plant flue gases with 500 to 1,000 ppm sulfur dioxide. These trials have not been successful in obtaining good conversion at tolerable pressure drops. In most instances, a fixed catalyst bed has had to be used to obtain 90 percent or greater conversion to sulfur trioxide. These fixed beds result in pressure drops of 15 inches of water column and greater and would represent appreciable power expenditures for the volume handled at power plants. To be practical, catalytic oxidation would probably have to be accomplished in a floating bed with a pressure drop of less than 4 inches of water column. Trials with catalysts injected into the gas stream have been disappointing in that conversion to SO_3 is normally below 50 percent.

If the oxidation process were perfected, it could be used in conjunction with baghouse particulate collectors or possibly with concentrated sulfuric acid scrubbers. An arrangement such as this would be expected to remove 90 percent or more of the sulfur oxides, depending principally upon the degree of oxidation. Any oxidation process would have to be preceded by a cloth filter or by a precipitator to remove materials that might poison the catalyst or contaminate the acid by-product. Vanadium and iron oxide catalysts would probably be preferred over platinum, which is readily poisoned by arsenic and halogens. Catalysts that are resistant to fouling would have an obvious advantage for this purpose.

Inhibiting Sulfur Trioxide Formation at Reduced Oxygen

Some operators report a definite reduction of sulfur trioxide and lowering of the dew point when combustion air is reduced almost to the stoichiometric fuel requirement. Crumley and Fletcher (1956) ran a series of laboratory tests that showed a reduction of sulfur trioxide as excess air was reduced from approximately 70 to 9 percent of the theoretical combustion requirement. More recently Glaubitz (1963) reported definite dew point lowering at 1 to 3 percent excess air, that is, 0.2 to 0.6 percent oxygen in flue gas. A significant fact

derived from these investigations is that large steam generators can be operated at flue gas oxygen concentrations as low as 0.2 percent without a marked decrease in combustion efficiency.

In Figure 387 oxygen concentrations in flue gases from oil-fired equipment are plotted against apparent dew points for fuels of 1.3, 2.4, and 3.2 percent sulfur. Note that dew point is a function of the fuel's sulfur content. This phenomenon is more pronounced at higher excess air rates. As excess air is reduced toward zero, the effect of fuel sulfur is diminished. At 0.2 percent oxygen, there is essentially no difference in dew points of any of the fuels. The resultant common dew point of 127°F at 0.2 percent oxygen, is approximately 200°F lower than the reported value for the highest sulfur fuel at 3.0 percent oxygen (15 percent excess air).

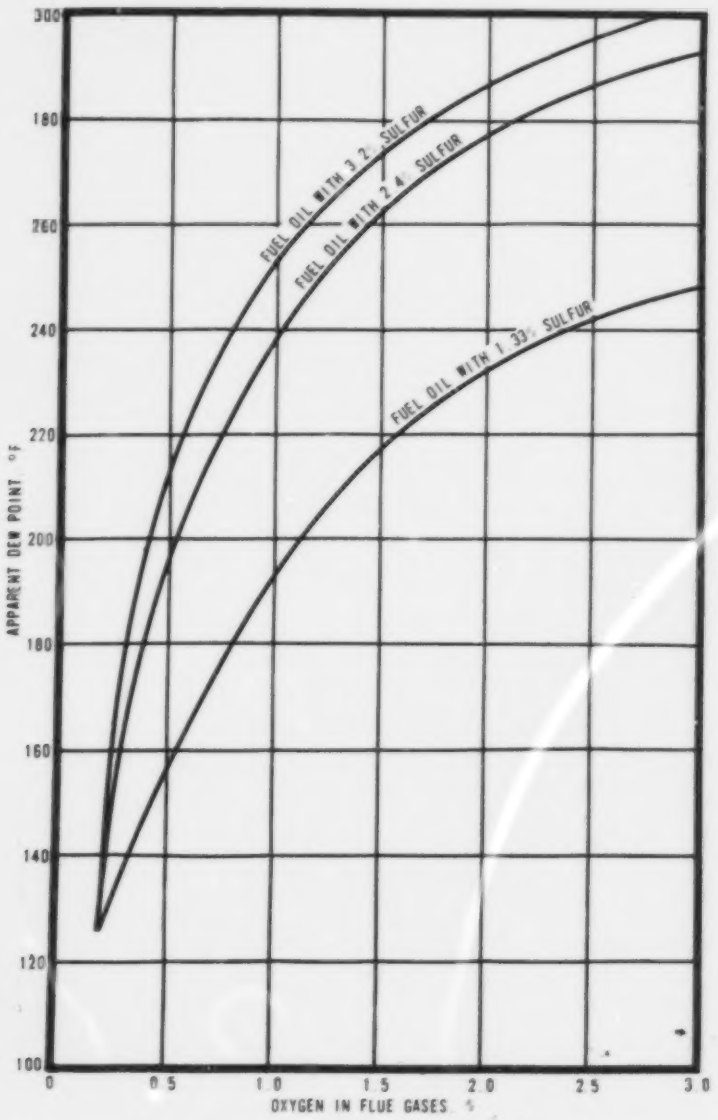


Figure 387. Dew point raising in an oil-fired boiler at varying oxygen concentrations (Glaubitz, 1963).

Others have confirmed that operation at 0.2 to 0.6 percent oxygen is feasible and materially lowers plume opacity. This operation also results in heavier concentrations of particulate matter, most of which is carbon. One operator reported that operation at 0.3 percent oxygen resulted in an increase in thermal efficiency of 1 to 2 percent over normal operation at 2 percent oxygen.

Operation at small oxygen concentrations warrants further investigation inasmuch as it would appear to provide benefits in terms of control of air pollution as well as economy of plant operation. Whether the increase of combustible contaminants is offset by the decrease in sulfur trioxide and visible emissions remains to be determined. This method also offers some promise of reducing nitrogen oxide concentrations in flue gases.

Controlling Oxides of Nitrogen

It is theoretically possible to reduce NO_x concentrations in combustion process flue gases by (1) modifying the burners or firebox, or both, to prevent its formation; (2) decomposing nitric oxide and possibly nitrogen dioxide back to the elements oxygen and nitrogen; or (3) scrubbing the effluent gases. Of the three possibilities, modifications of the combustion equipment have been shown to be the most effective and probably offer the most promise of further NO_x reduction at combustion sources. No practical methods of decomposition or scrubbing are presently available.

A furnace modification has been developed by which steam generator NO_x emissions can be reduced by 40 to 50 percent. These designs are relatively new, and further refinements can reasonably be expected to be made by which NO_x concentrations can be reduced to a significantly larger degree. Successful methods tend to lower maximum firebox temperatures, promote faster flame cooling, and reduce oxygen concentrations in the highest temperature zones.

Two-Stage Combustion

One of the most effective NO_x-reducing methods applied to steam generators has been the splitting of combustion air in the manner described by Barnhart and Diehl (1960) as two-stage combustion. With two-stage combustion, only 90 to 95 percent of the theoretical combustion air requirement is injected at the burner. The remaining air is introduced a few feet downstream of the burner to complete combustion over a somewhat longer zone. With this arrangement, the total excess air rate is held to the same figure used during normal firing, that is, about 10 percent. This delayed air introduction was found to reduce

NO_x concentrations in flue gases by 40 to 50 percent. Large steam generators have been observed to operate on two-stage combustion without any measurable loss in combustion efficiency on either gas or oil firing.

A typical front-fired boiler using two-stage combustion is shown in Figure 388. The major portion of the combustion air requirement is introduced at the burners in the normal manner, while auxiliary air is introduced downstream after the last (upper) row of burners.

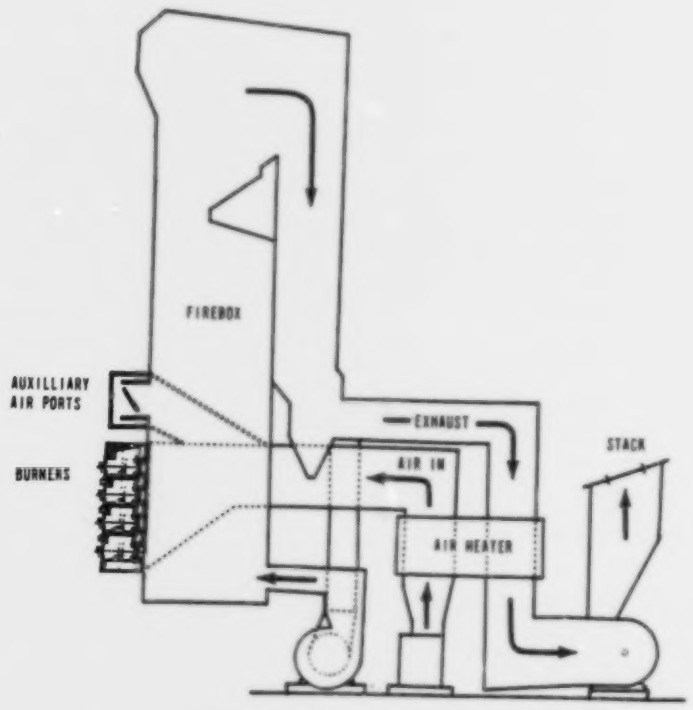


Figure 388. A front-fired boiler modified to provide two-stage combustion.

The data in Table 153 show the effect of two-stage combustion when natural gas and residual fuel oil are fired. The maximum NO_x reduction was achieved on oil firing with only 90 percent of the theoretical air requirement introduced through the burner. On a percentage basis, the reduction that can be achieved on oil firing is usually somewhat higher than the comparable reduction on gas firing. This would appear to be due to the flame temperature differential between the two fuels.

Corner-Fired Steam Generators

A furnace design that provides an NO_x reduction comparable to that provided by two-stage combustior is the so-called corner-fired or tangentially fired steam generator. A boiler incorporating this design is shown in Figures 389 and 390. The corner-fired boiler is a major deviation from conventional front-fired units in that the number of burner assemblies is considerably less than with front-fired units, in which multiple-burner assemblies are used. Single-burner assemblies are mounted in the four corners of the furnace, and there are usually three or four burner ports in a vertical line in each assembly. The burners are designed to provide a relatively long, luminous flame. Thus, the flames from each burner can "see" a considerably larger area of wall heat transfer surfaces than those from burners in front-fired units can. As a result, maximum flame temperatures are apparently lowered enough to reduce nitric oxide formation considerably. Corner-fired boilers also employ somewhat higher water circulation rates through furnace tubes. This probably provides faster cooling of gases in the furnace.

Tangentially or corner-fired steam generators are reported by Sensenbaugh and Jonakin (1960) to result in NO_x concentrations roughly equivalent to those of units equipped with two-stage combustion. Table 154 lists NO_x concentrations from corner-fired boilers and from front-fired units of approximately the same size. It can be seen that tangential firing resulted in 53 percent less NO_x on gas firing and 48 percent less NO_x on oil firing than conventional steam generators without NO_x-reducing features could achieve. From both

Table 153. EFFECT OF TWO-STAGE COMBUSTION ON NO_x CONCENTRATIONS FROM A LARGE STEAM GENERATOR AT NORMAL FULL LOAD (Barnhart and Diehl, 1960)

Fuel	NO_x concentration	Two-stage combustion		
	All air through burners, ppm by vol	Air through burners, % of theoretical[a]	NO_x, ppm by vol	Reduction, %
Oil and gas combined	525	95	385	27
Oil	580	90	305	47

[a] The remaining 15 to 20 percent of combustion air was injected a few feet downstream of the burner to provide an excess air ratio of 7 to 10 percent.

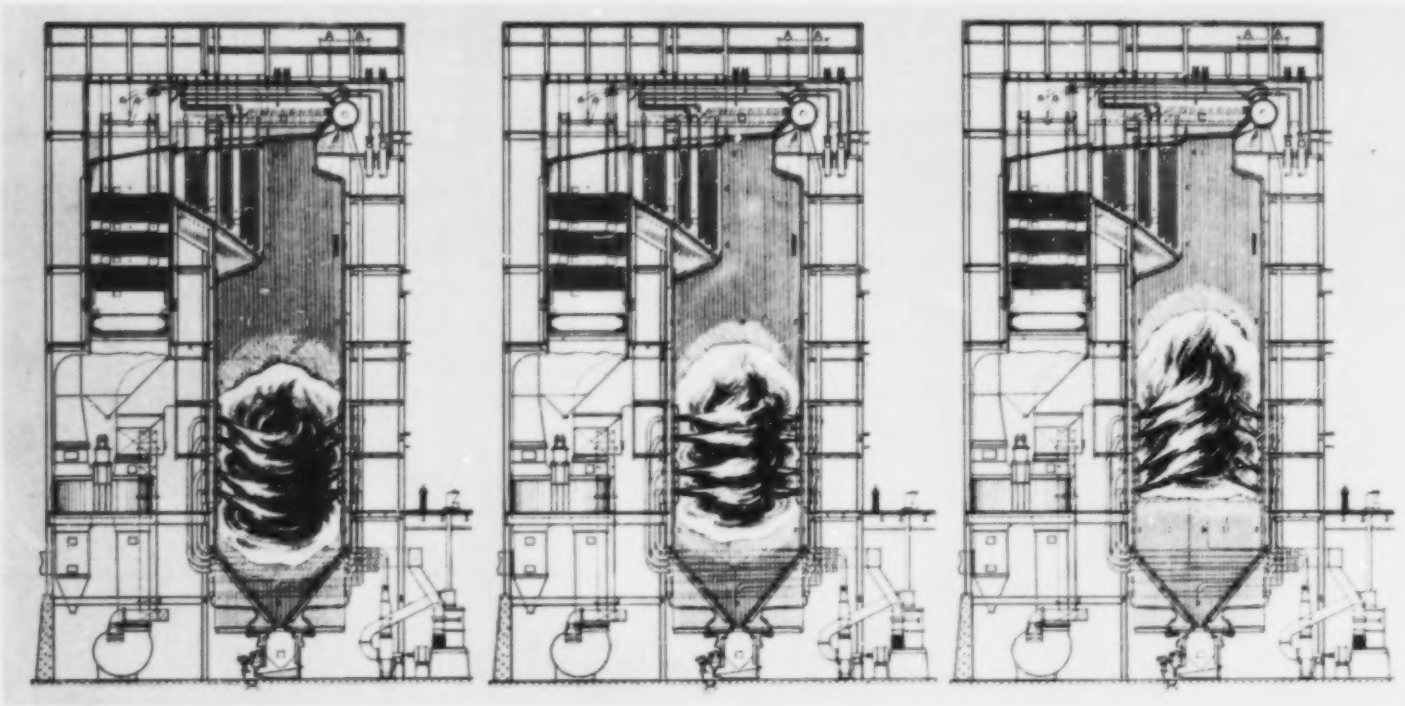


Figure 389. A corner-fired steam generator with tilting burners positioned for varying load and superheat (Combustion Engineering, Inc., New York, N.Y.).

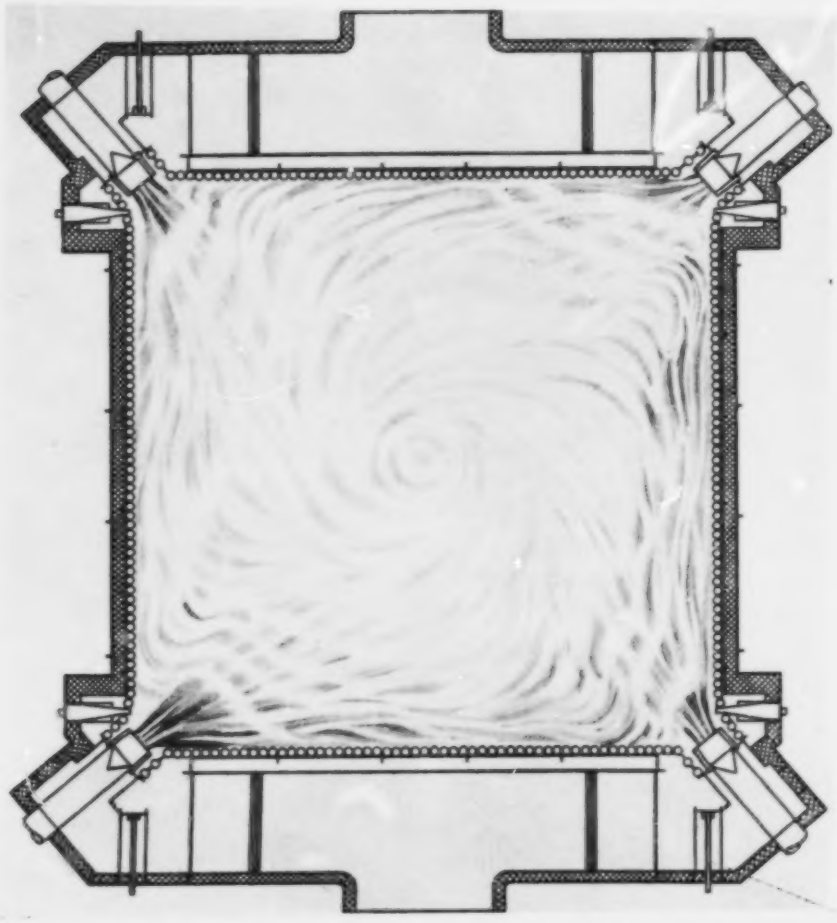


Figure 390. Cross-section of a corner-fired boiler firebox (Combustion Engineering, Inc., New York, N.Y.).

corner-fired and front-fired units NO_x emissions were lower on gas firing than on oil firing, the differences ranging from 24 to 59 percent.

A corner-fired furnace represents a major portion of the steam generator design. It cannot be built into existing equipment as two-stage combustion can.

Lowering Excess Air

As pointed out earlier, NO_x concentrations can be lowered 20 to 30 percent by reducing excess air rates. The minimum possible oxygen concentration is about 0.2 percent (approximately 1 percent excess air). Nevertheless, simple lowering of excess air does not appear to be as effective nor as explosion proof as two-stage combustion is. It is doubtful, therefore, that this practice will find much acceptance solely for NO_x reduction. If, however, low-oxygen combustion were used to inhibit sulfur trioxide formation, some lowering of oxides of nitrogen could be expected as a bonus.

Eliminating Air Preheat

An obvious method of reducing NO_x at large steam generators is the elimina-

Table 154. A COMPARISON OF NO_x CONCENTRATIONS IN PPM BY VOLUME FROM CORNER-FIRED AND FROM FRONT-FIRED STEAM GENERATORS[a] AT NORMAL FULL LOAD
(Sensenbaugh and Jonakin, 1960)

Unit	Firing	Fuel	
		Gas	Oil
A	Front	520	685
B	Front	290	567
C	Front	319	505
D	Front	---	482
E	Front	226	---
F	Corner	164	362
G	Corner	157	309
H	Corner	---	209

[a]The front-fired steam generators were not designed or operated to minimize NO_x.

tion of combustion air preheaters. Reducing air temperatures by 400° to 600°F would lower maximum firebox temperatures by an almost equal increment. The lowering of flame temperature would be expected to reduce nitric oxide formation considerably, though there are few data to support or refute the theory. As noted earlier, NO_x reductions of 12 to 75 percent have been reported. The only available data have been measured at pilot equipment. What NO_x reduction could be expected from operating large combustion equipment without air preheat is not known.

Combustion air preheaters are found on almost all boilers and heaters of 100 million Btu per hour and greater gross input. They are located on the discharge of the equipment just ahead of the stack. Combustion gas temperatures are reduced from about 850° to about 300°F at the point of discharge. Air temperatures are increased by a comparable increment of 450° to 600°F. Obviously, combustion products could not be discharged at 800° to 900°F without a gross sacrifice of thermal efficiency. This heat can, however, be recovered in water or low-pressure steam rather than air. If the residual enthalpy were used to heat or vaporize water, combustion air could be introduced to the furnace at ambient temperature, and thermal efficiency would not suffer.

Other Means of Lowering Flame Temperature

Several other methods of lowering flame temperature are possible. Most of these have definite economic drawbacks and have not been incorporated into large combustion equipment. Firebox temperatures can be lowered by injecting water, steam, or dilution gases at the burners. All these possibilities would reduce thermal efficiencies to a greater degree than could be tolerated at power plants.

NO_x could theoretically be reduced by adding water-cooled heat transfer surfaces in the immediate vicinity of the burners. An arrangement such as this would probably be most effective if the cooling surfaces were spaced between burners so that flames could "see" more cooling surfaces. Any arrangement of this sort would necessarily require rapid circulation through the heat exchangers, more so than that provided in common waterwalls of furnaces. No data are available on the effectiveness of this technique.

Catalytic Decomposition of NO_x

Attempts have been made to decompose NO and NO_2 back to the elements, nitrogen and oxygen. As noted earlier in this chapter, NO equilibrium concentrations are still appreciable (100 ppm) in combustion gases at 1,800°F. To be acceptable, decomposition would necessarily have to be accomplished well below 2,000°F. In this range, decomposition is extremely slow without catalysis.

Faith et al. (1957), tested the effectiveness of a series of commercial and specially prepared catalysts in decomposing NO-NO_2 mixtures. None of the catalysts were judged sufficiently active to produce more than a slight decomposition.

Catalytic decomposition as a control method would appear to depend solely upon the development of a suitable catalyst. When and if this catalyst is found, it will probably have to be used at temperatures above 1,000°F. Thus, it would have to be installed ahead of the air preheater, and possibly ahead of the tube sections as well.

Scrubbing NO_x

Nitrogen dioxide can be absorbed in water and alkaline solutions though removal efficiencies are generally low. NO_2 reacts with water to form nitric acid and nitrous acid or nitric oxide. Peters (1955b) reports removal efficiencies as high as 50 percent at combined NO_2 and N_2O_4 concentrations of 2 percent (20,000 ppm). NO_2 removal decreases greatly, however, at lesser concentrations, dropping to 10 percent at 2,000 ppm (Peters, 1955b).

Nitric oxide is much less reactive than NO_2 is, and scrubbing methods are even less successful. Even if more efficient scrubbing solutions were found, NO would probably have to be oxidized first to NO_2 to accomplish an adequate cleanup. Scrubbing of oxides of nitrogen appears to have most of the economic disadvantages of scrubbing of sulfur dioxide plus an inherent low removal efficiency.

Adsorption of NO_x

Some laboratory investigations have been made into the adsorption of NO_2 on activated carbon and silica gel. Both of these media adsorb measurable amounts of NO_2, but carbon appears to offer more promise in the control of emissions from combustion equipment.

Silica gel is reported to provide efficiencies of close to 90 percent in adsorbing NO_2 and N_2O_4 at 70°F in large concentrations, that is, about 2 percent by volume. At smaller concentrations, efficiencies decrease, becoming only about 30 percent at 0.20 percent (2,000 ppm). Moreover, available silica gels have extremely low capacities for NO_2 at these conditions (Peters, 1955b). In short, adsorption on silica gel appears impractical in light of existing data.

Haagen-Smit (1958) noted that oxides of nitrogen are adsorbed on activated carbon ahead of sulfur dioxide. Collected NO_x is then displaced from the carbon as it becomes saturated with SO_2.

The Reinluft process, noted earlier in the chapter, is used to adsorb both SO_2 and NO_x in a moving bed of low-grade activated charcoal. It is reported to provide up to 85 percent removal of both SO_2 and NO_x, producing sulfuric and nitric acids as by-products. This process is still in the experimental stage and has not yet been proved satisfactory for large steam generators. Nevertheless, it is one of the few methods that offers hope of high-efficiency control at combustion sources.

CHAPTER 10

PETROLEUM EQUIPMENT

GENERAL INTRODUCTION

ROBERT C. MURRAY
Senior Air Pollution Engineer

WASTE-GAS DISPOSAL SYSTEMS

DONALD F. WALTERS*
Intermediate Air Pollution Engineer

STORAGE VESSELS

ROBERT C. MURRAY
Senior Air Pollution Engineer

LOADING FACILITIES

ROBERT H. KINSEY†
Air Pollution Engineer

CATALYST REGENERATION

STANLEY T. CUFFE*
Air Pollution Engineer

OIL-WATER EFFLUENT SYSTEMS

ROBERT H. KINSEY
Air Pollution Engineer

PUMPS

ROBERT H. KINSEY
Air Pollution Engineer

AIRBLOWN ASPHALT

ROBERT H. KINSEY
Air Pollution Engineer

VALVES

ROBERT H. KINSEY
Air Pollution Engineer

COOLING TOWERS

ROBERT C. MURRAY
Senior Air Pollution Engineer

MISCELLANEOUS SOURCES

ROBERT H. KINSEY
Air Pollution Engineer

*Now with National Center for Air Pollution Control, Public Health Service, U.S. Department of Health, Education, and Welfare, Cincinnati, Ohio.
†Now with Lockheed Missiles Systems Company, 1111 Lockheed Way, Sunnyvale, California.

BLANK PAGE

CHAPTER 10

PETROLEUM EQUIPMENT

GENERAL INTRODUCTION

Operations of the petroleum industry can logically be divided into production, refining, and marketing. Production includes locating and drilling oil wells, pumping and pretreating the crude oil, recovering gas condensate, and shipping these raw products to the refinery or, in the case of gas, to commercial sales outlets. Refining, which extends to the conversion of crude to a finished salable product, includes oil refining and the manufacture of various chemicals derived from petroleum. This chemical manufacture is often referred to as the petrochemical industry. Marketing involves the distribution and the actual sale of the finished products. These activities and their sources of air pollution are briefly discussed in this introduction. In the remainder of the chapter, they are discussed much more thoroughly, and adequate air pollution controls are recommended.

CRUDE OIL PRODUCTION

The air contaminants emitted from crude oil production consist chiefly of the lighter saturated hydrocarbons. The main sources are process equipment and storage vessels. Hydrogen sulfide gas may be an additional contaminant in some production areas. Internal combustion equipment, mostly natural gas-fired compressors, contributes relatively negligible quantities of sulfur dioxide, nitrogen oxides, and particulate matter. Potential individual sources of air contaminants are shown in Table 155.

Contribution of air contaminants from crude-oil production varies widely with location and concentration of producing facilities. In isolated or scattered locations, many of the sources cannot be controlled feasibly. Control and pretreatment facilities such as natural gasoline plants are more likely to be located in more developed or highly productive areas. These factors are significant in determining where air contaminant emissions from production equipment must be minimized by proper use of air pollution control equipment. Control equipment for the various air pollution sources associated with crude-oil production are listed in Table 155. Their application can usually result in economic savings.

REFINING

Oil companies have installed or modified equipment not only to prevent economic losses but also to try to improve community relations, prevent fire hazards, and comply with air pollution laws. The air contaminants emitted from equipment associated with oil refining include hydrocarbons, carbon monoxide, sulfur and nitrogen compounds, malodorous materials, particulate matter, aldehydes, organic acids, and ammonia. The potential sources of these pollutants are shown in Table 156.

Flares and Blowdown Systems

To prevent unsafe operating pressures in process units during shutdowns and startups and to handle miscellaneous hydrocarbon leaks, the refinery must provide a means of venting hydrocarbon vapors safely. Either a properly sized elevated flare using steam injection or a series of venturi burners actuated by pressure increases is satisfactory. Good instrumentation and properly balanced steam-to-hydrocarbon ratios are prime factors in the design of a safe, smokeless flare.

Pressure Relief Valves

In refinery operations, process vessels are protected from overpressure by relief valves. These pressure-relieving devices are normally spring-loaded valves. Corrosion or improper reseating of the valve seat results in leakage. Proper maintenance through routine inspections, or use of rupture discs, or manifolding the discharge side to vapor recovery or to a flare minimizes air contamination from this source.

Storage Vessels

Tanks used to store crude oil and volatile petroleum distillates are a large potential source of hydrocarbon emissions. Hydrocarbons can be discharged to the atmosphere from a storage tank as a result of diurnal temperature changes, filling operations, and volatilization. Control efficiencies of 85 to 100 percent can be realized by using properly designed vapor recovery or disposal systems, floating-roof tanks, or pressure tanks.

Table 155. SOURCES AND CONTROL OF AIR CONTAMINANTS FROM CRUDE-OIL PRODUCTION FACILITIES

Phase of operation	Source	Contaminant	Acceptable control
Well drilling, pumping	Gas venting for production rate test	Methane	Smokeless flares, wet-gas-gathering system
	Oil well pumping	Light hydrocarbon vapors	Proper maintenance
	Effluent sumps	Hydrocarbon vapors, H_2S	Replacement with closed vessels connected to vapor recovery
Storage, shipment	Gas-oil separators	Light hydrocarbon vapors	Relief to wet-gas-gathering system
	Storage tanks	Light hydrocarbon vapors, H_2S	Vapor recovery, floating roofs, pressure tanks, white paint
	Dehydrating tanks	Hydrocarbon vapors, H_2S	Closed vessels, connected to vapor recovery
	Tank truck loading	Hydrocarbon vapors	Vapor return, vapor recovery, vapor incineration, bottom loading
	Effluent sumps	Hydrocarbon vapors	Replacement with closed vessels connected to vapor recovery
	Heaters, boilers	H_2S, HC, SO_2, NO_x, particulate matter	Proper operation, use of gas fuel
Compression, absorption, dehydrating, water treating	Compressors, pumps	Hydrocarbon vapors, H_2S	Mechanical seals, packing glands vented to vapor recovery
	Scrubbers, KO pots	Hydrocarbon vapors, H_2S	Relief to flare or vapor recovery
	Absorbers, fractionators, strippers	Hydrocarbon vapors	Relief to flare or vapor recovery
	Tank truck loading	Hydrocarbon vapors, H_2S	Vapor return, vapor recovery, vapor incineration, bottom loading
	Gas odorizing	H_2S mercaptans	Positive pumping, adsorption
	Waste-effluent treating	Hydrocarbon vapors	Enclosed separators, vapor recovery or incineration
	Storage vessels	Hydrocarbon vapors, H_2S	Vapor recovery, vapor balance, floating roofs
	Heaters, boilers	Hydrocarbon, SO_2, NO_x, particulate matter	Proper operation, substitute gas as fuel

Bulk-Loading Facilities

The filling of vessels used for transport of petroleum products is potentially a large source of hydrocarbon emissions. As the product is loaded, it displaces gases containing hydrocarbons to the atmosphere. An adequate method of preventing these emissions consists of collecting the vapors by enclosing the filling hatch and piping the captured vapors to recovery or disposal equipment. Submerged filling and bottom loading also reduces the amount of displaced hydrocarbon vapors.

Catalyst Regenerators

Modern refining processes include many operations using solid-type catalysts. These catalysts become contaminated with coke buildup during operation and must be regenerated or discarded. For certain processes to be economically feasible, for example, catalytic cracking, regeneration of the catalyst is a necessity and is achieved by burning off the coke under controlled combustion conditions. The resulting flue gases may contain catalyst dust, hydrocarbons, and other impurities originating in the charging stock, as well as the products of combustion.

The dust problem encountered in regeneration of moving-bed-type catalysts requires control by water scrubbers and cyclones, cyclones and precipitators, or high-efficiency cyclones, depending upon the type of catalyst, the process, and the regenerator conditions. Hydrocarbons, carbon monoxide, ammonia, and organic acids can be controlled effectively by incineration in carbon monoxide waste-heat boilers. The waste-heat boiler offers a secondary control feature for plumes emitted from fluid catalytic cracking units. This type of visible plume, shown in Figure 391, whose degree of opacity is dependent upon atmospheric humidity, can be eliminated by using the carbon monoxide waste-heat boiler.

Table 156. POTENTIAL SOURCES OF EMISSIONS FROM OIL REFINING

Type of emission	Potential source
Hydrocarbons	Air blowing, barometric condensers, blind changing, blowdown systems, boilers, catalyst regenerators, compressors, cooling towers, decoking operations, flares, heaters, incinerators, loading facilities, processing vessels, pumps, sampling operations, tanks, turnaround operations, vacuum jets, waste-effluent-handling equipment
Sulfur oxides	Boilers, catalyst regenerators, decoking operations, flares, heaters, incinerators, treaters, acid sludge disposal
Carbon monoxide	Catalyst regenerators, compressor engines, coking operations, incinerators
Nitrogen oxides	Boilers, catalyst regenerators, compressor engines, flares
Particulate matter	Boilers, catalyst regenerators, coking operations, heaters, incinerators
Odors	Air blowing, barometric condensers, drains, process vessels, steam blowing, tanks, treaters, waste-effluent-handling equipment
Aldehydes	Catalyst regenerators, compressor engines
Ammonia	Catalyst regenerators

Figure 391. A fluid catalytic cracking unit as a source of a visible plume. Use of a carbon monoxide waste-heat boiler eliminates this plume formation.

Other processes in refining operations employ liquid or solid catalysts. Regenerating some of these catalysts at the unit is feasible. Other catalysts are consumed or require special treatment by their manufacturer. Where regeneration is possible, a closed system can be effected to minimize the release of any air contaminants by venting the regenerator effluent to the firebox of a heater.

Effluent-Waste Disposal

Waste water, spent acids, spent caustic and other waste liquid materials are generated by refining operations and present disposal problems. The waste water is processed through clarification units or gravity separators. Unless adequate control measures are taken, hydrocarbons contained in the waste water are emitted to the atmosphere. Acceptable control is achieved by venting the clarifier to vapor recovery and enclosing the separator with a floating roof or a vapor-tight cover. In the latter case, the vapor section should be gas blanketed to prevent explosive mixtures and fires. Spent waste materials can be recovered as acids or phenolic compounds, or hauled to an acceptable disposal site (ocean or desert).

Pumps and Compressors

Pumps and compressors required to move liquids and gases in the refinery can leak product at the point of contact between the moving shaft and stationary casing. Properly maintained packing glands or mechanical seals minimize the emissions from pumps. Compressor glands can be vented to a vapor recovery system or smokeless flare.

The internal combustion engines normally used to drive the compressors are fueled by natural or refinery process gas. Even with relatively high combustion efficiency and steady load conditions, some fuel can pass through the engine unburned. Nitrogen oxides, aldehydes, and sulfur oxides can also be found in the exhaust gases. Control methods for reducing these contaminants are being studied.

Air-Blowing Operations

Venting the air used for "brightening" and agitation of petroleum products or oxidation of asphalt results in a discharge of entrained hydrocarbon vapors and mists, and malodorous compounds. Mechanical agitators that replace air agitation can reduce the volumes of these emissions. For the effluent fumes from asphalt oxidation, incineration gives effective control of the hydrocarbons and malodors.

Pipeline Valves and Flanges, Blind Changing, Process Drains

Liquid and vapor leaks can develop at valve stems as a result of heat, pressure, friction, corrosion, and vibration. Regular equipment inspections followed by adequate maintenance can keep losses at a minimum. Leaks at flange connections are negligible if the connections are properly installed and maintained. Installation or removal of pipeline blinds can result in spillage of some product. A certain amount of this spilled product evaporates regardless of drainage and flushing facilities. Special pipeline blinds have, however, been developed to reduce the amount of spillage.

In refinery operation, condensate water and flushing water must be drained from process equipment. These drains also remove liquid leakage or spills and water used to cool pump glands. Modern refining designs provide wastewater-effluent systems with running-liquid-sealed traps and liquid-sealed and covered junction boxes. These seals keep the amount of liquid hydrocarbons exposed to the air at a minimum and thereby reduce hydrocarbon losses.

Cooling Towers

The large amounts of water used for cooling are conserved by recooling the water in wooden towers. Cooling is accomplished by evaporating part of this water. Any hydrocarbons that might be entrained or dissolved in the water as a result of leaking heat exchange equipment are readily discharged to the atmosphere. Proper design and maintenance of heat exchange equipment minimizes this loss. Advancement of the fin-fan cooling equipment has also replaced the need of the conventional cooling tower in many instances. Process water that has come into contact with a hydrocarbon stream or has otherwise been contaminated with odorous material should not be piped to a cooling tower.

Vacuum Jets and Barometric Condensers

Some process equipment is operated at less than atmospheric pressure. Steam-driven vacuum jets and barometric condensers are used to obtain the desired vacuum. The lighter hydrocarbons that are not condensed are discharged to the atmosphere unless controlled. These hydrocarbons can be completely controlled by incinerating the discharge. The barometric hot well can also be enclosed and vented to a vapor disposal system. The water of the hot well should not be turned to a cooling tower.

EFFECTIVE AIR POLLUTION CONTROL MEASURES

Control of air contaminants can be accomplished by process change, installation of control equipment, improved housekeeping, and better equipment maintenance. Some combination of these often proves the most effective solution. Table 157 indicates various methods of controlling most air pollution sources encountered in the oil refinery. These techniques are also applicable to petrochemical operations. Most of these controls result in some form of economic saving.

MARKETING

An extensive network of pipelines, terminals, truck fleets, marine tankers, and storage and loading equipment must be used to deliver the finished petroleum product to the user. Hydrocarbon emissions from the distribution of products derive principally from storage vessels and filling operations. Additional hydrocarbon emissions may occur from pump seals, spillage, and effluent-water separators. Table 158 lists practical methods of minimizing these emissions from this section of the industry.

WASTE-GAS DISPOSAL SYSTEMS

INTRODUCTION

Large volumes of hydrocarbon gases are produced in modern refinery and petrochemical plants. Generally, these gases are used as fuel or as raw material for further processing. In the past, however, large quantities of these gases

Table 157. SUGGESTED CONTROL MEASURES FOR REDUCTION OF AIR CONTAMINANTS FROM PETROLEUM REFINING

Source	Control method
Storage vessels	Vapor recovery systems; floating-roof tanks; pressure tanks; vapor balance; painting tanks white
Catalyst regenerators	Cyclones - precipitator - CO boiler; cyclones - water scrubber; multiple cyclones
Accumulator vents	Vapor recovery; vapor incineration
Blowdown systems	Smokeless flares - gas recovery
Pumps and compressors	Mechanical seals; vapor recovery; sealing glands by oil pressure; maintenance
Vacuum jets	Vapor incineration
Equipment valves	Inspection and maintenance
Pressure relief valves	Vapor recovery; vapor incineration; rupture discs; inspection and maintenance
Effluent-waste disposal	Enclosing separators; covering sewer boxes and using liquid seal; liquid seals on drains
Bulk-loading facilities	Vapor collection with recovery or incineration; submerged or bottom loading
Acid treating	Continuous-type agitators with mechanical mixing; replace with catalytic hydrogenation units; incinerate all vented cases; stop sludge burning
Acid sludge storage and shipping	Caustic scrubbing; incineration; vapor return system; disposal at sea
Spent-caustic handling	Incineration; scrubbing
Doctor treating	Steam strip spent doctor solution to hydrocarbon recovery before air regeneration; replace treating unit with other, less objectionable units (Merox)
Sour-water treating	Use sour-water oxidizers and gas incineration; conversion to ammonium sulfate
Mercaptan disposal	Conversion to disulfides; adding to catalytic cracking charge stock; incineration; using material in organic synthesis
Asphalt blowing	Incineration; water scrubbing (nonrecirculating type)
Shutdowns, turnarounds	Depressure and purge to vapor recovery

Table 158. SOURCES AND CONTROL OF HYDROCARBON LOSSES FROM PETROLEUM MARKETING

Source	Control method
Storage vessels	Floating-roof tanks; vapor recovery; vapor disposal; vapor balance; pressure tanks; painting tanks white
Bulk-loading facilities	Vapor collection with recovery or incineration; submerged loading, bottom loading
Service station delivery	Vapor return; vapor incineration
Automotive fueling	Vapor return
Pumps	Mechanical seals; maintenance
Separators	Covers; use of fixed-roof tanks
Spills, leaks	Maintenance; proper housekeeping

were considered waste gases, and along with waste liquids, were dumped to open pits and burned, producing large volumes of black smoke. With modernization of processing units, this method of waste-gas disposal, even for emergency gas releases, has become less acceptable to the industry. Moreover, many local governments have adopted or are contemplating ordinances limiting the opacity of smoke from combustion processes.

Nevertheless, petroleum refineries are still faced with the problem of safe disposal of volatile liquids and gases resulting from scheduled shutdowns and sudden or unexpected upsets in process units. Emergencies that can cause the sudden venting of excessive amounts of gases and vapors include fires, compressor failures, overpressures in process vessels, line breaks, leaks, and power failures. Uncontrolled releases of large volumes of gases also constitute a serious safety hazard to personnel and equipment.

A system for disposal of emergency and waste refinery gases consists of a manifolded pressure-relieving or blowdown system, and a blowdown recovery system or a system of flares for the combustion of the excess gases, or both. Many refineries, however, do not operate blowdown recovery systems. In addition to disposing of emergency and excess gas flows, these systems are used in the evacuation of units during shutdowns and turnarounds. Normally a unit is shut down by depressuring into a fuel gas or vapor recovery system with further depressuring to essentially atmospheric pressure by venting to a low-pressure flare system. Thus, overall emissions of refinery hydrocarbons are substantially reduced.

Refinery pressure-relieving systems, commonly called blowdown systems, are used primarily to ensure the safety of personnel and protect equipment in the event of emergencies such as process upset, equipment failure, and fire. In addition, a properly designed pressure relief system permits substantial reduction of hydrocarbon emissions to the atmosphere.

The equipment in a refinery can operate at pressures ranging from less than atmospheric to 1,000 psig and higher. This equipment must be designed to permit safe disposal of excess gases and liquids in case operational difficulties or fires occur. These materials are usually removed from the process area by automatic safety and relief valves, as well as by manually controlled valves, manifolded to a header that conducts the material away from the unit involved. The preferred method of disposing of the waste gases that cannot be recovered in a blowdown recovery system is by burning in a smokeless flare. Liquid blowdowns are usually conducted to appropriately designed holding vessels and reclaimed.

A blowdown or pressure-relieving system consists of relief valves, safety valves, manual bypass valves, blowdown headers, knockout vessels, and holding tanks. A blowdown recovery system also includes compressors and vapor surge vessels such as gas holders or vapor spheres. Flares are usually considered as part of the blowdown system in a modern refinery.

The pressure-relieving system can be used for liquids or vapors or both. For reasons of economy and safety, vessels and equipment dis-

charging to blowdown systems are usually segregated according to their operating pressure. In other words, there is a high-pressure blowdown system for equipment working, for example, above 100 psig, and low-pressure systems for those vessels with working pressures below 100 psig. Butane and propane are usually discharged to a separate blowdown drum, which is operated above atmospheric pressure to increase recovery of liquids. Usually a direct-contact type of condenser is used to permit recovery of as much hydrocarbon liquid as possible from the blowdown vapors. The noncondensables are burned in a flare.

A pressure-relieving system used in one modern petroleum refinery is shown in Figure 392. This system is used not only as a safety measure but also as a means of reducing the emission of hydrocarbons to the atmosphere. This installation actually includes four separate collecting systems as follows: (1) The low-pressure blowdown system for vapors from equipment with working pressure below 100 psig, (2) the high-pressure blowdown system for vapors from equipment with working pressures above 100 psig, (3) the liquid blowdown system for liquids at all pressures, and (4) the light-ends blowdown for butanes and lighter hydrocarbon blowdown products.

The liquid portion of light hydrocarbon products released through the light-ends blowdown system is recovered in a drum near the flare. A backpressure of 50 psig is maintained on the drum, which minimizes the amount of vapor that vents through a backpressure regulator to the high-pressure blowdown line. The high-pressure, low-pressure, and liquid-blowdown systems all discharge into the main blowdown vessel. Any entrained liquid is dropped out and pumped to a storage tank for recovery. Offgas from this blowdown drum flows to a vertical vessel with baffle trays in which the gases are contacted directly with water, which condenses some of the hydrocarbons and permits their recovery. The overhead vapors from this so-called sump tank flow to the flare system manifold for disposal by burning in a smokeless flare system.

The unique blowdown system shown in Figure 393 was installed primarily as an air pollution control measure. The system serves a delayed cok-

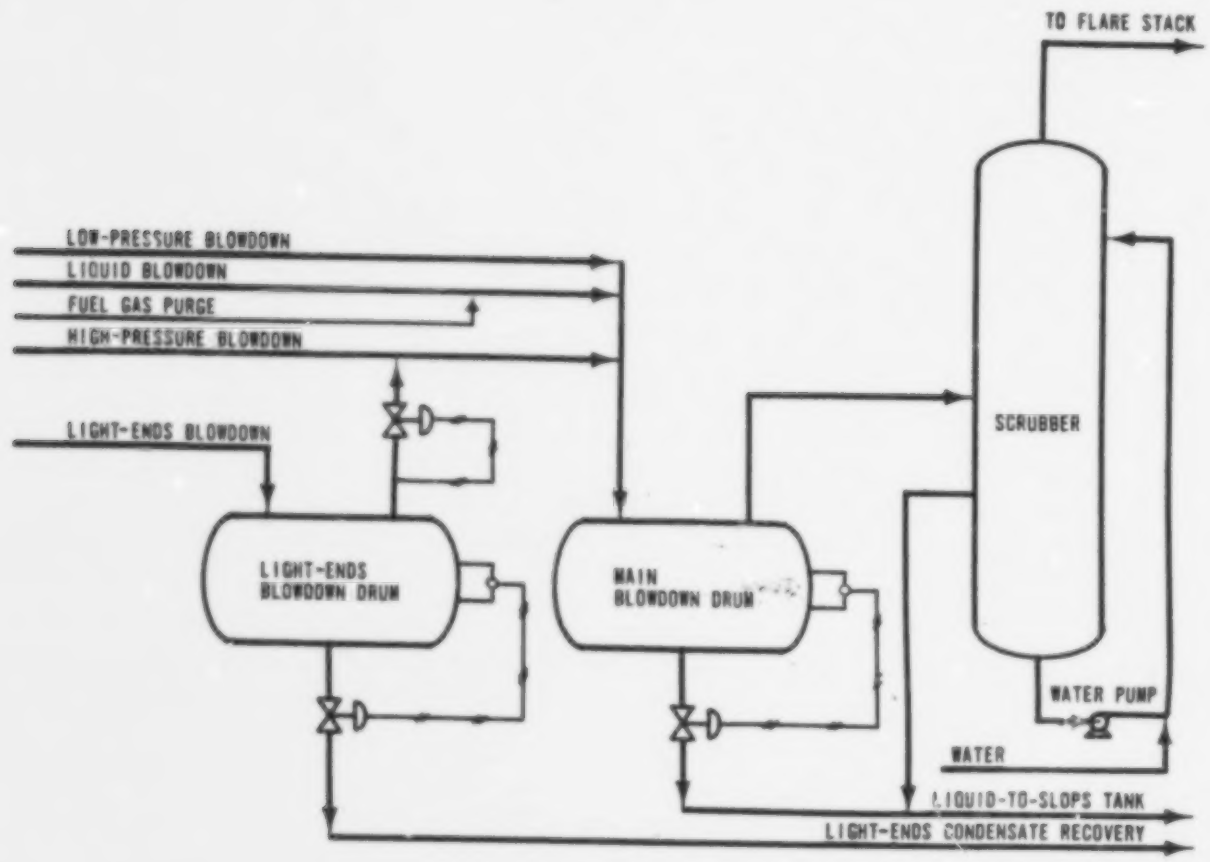


Figure 392. Typical modern refinery blowdown system.

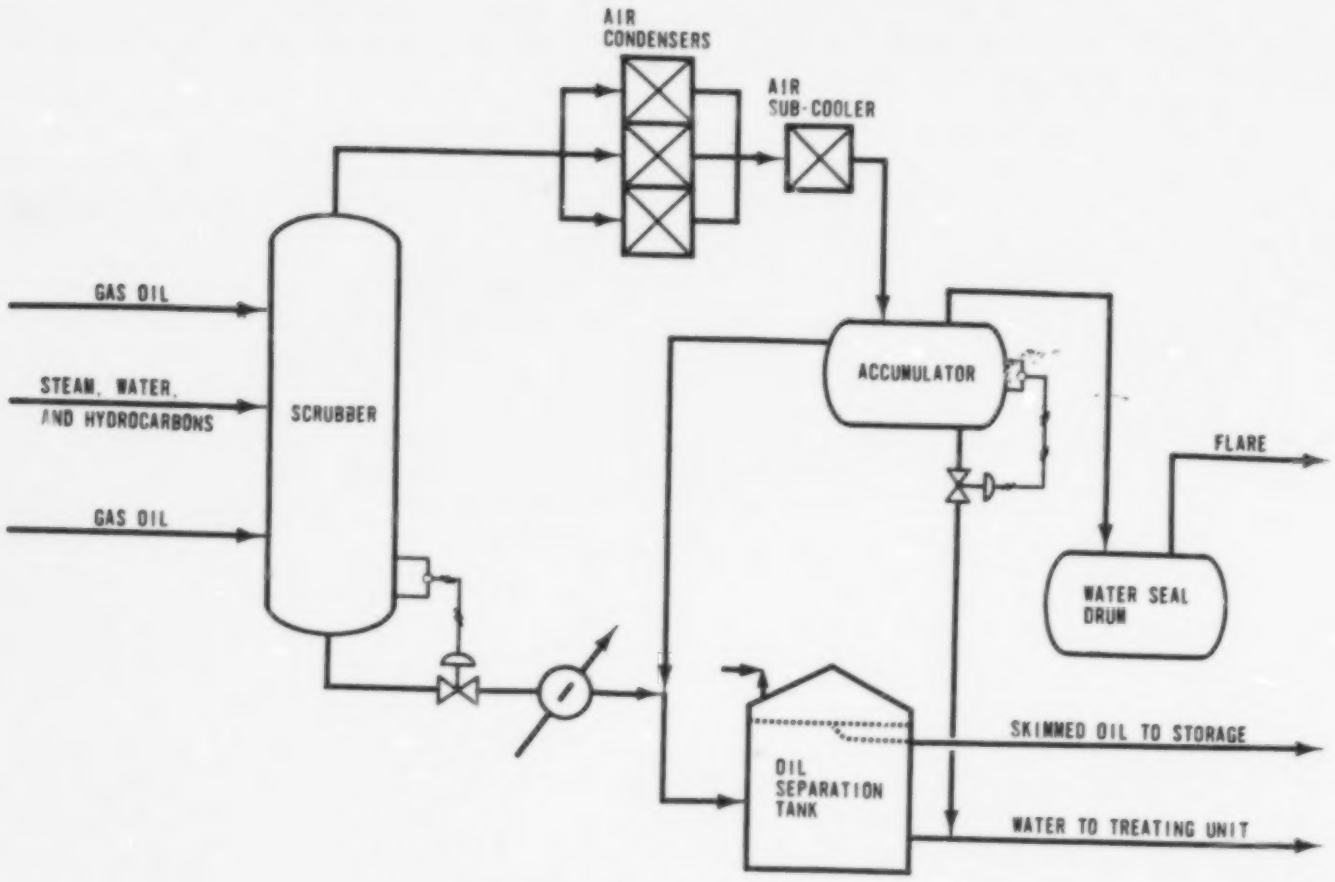


Figure 393. Coke drum blowdown system.

ing unit. In this process, each drum is taken off the line as it is filled with coke. The drum is then purged with steam and cooled with water. The steam-water-hydrocarbon mixture flows to a gas oil scrubber whose primary purpose is to remove entrained coke fines. At the same time some heavier hydrocarbons are condensed, and the mixture is pumped to a settling tank. The scrubbed gases flow to an air-cooled condenser and then through an air-cooled subcooler to an accumulator drum.

The air condenser sections are controlled by temperature and used as needed. The design outlet temperature range of the condensers is 212° to 270°F, and about 200°F for the subcooler.

The oil layer in the accumulator is skimmed off and pressured to the oil-settling tank while the water phase is sewered. Offgas flows through a water seal to a smokeless elevated flare. The oil-settling tank is a 3,000-barrel fixed-roof tank equipped with an oil skimmer. The oil phase is pumped to storage, and the water is sewered for further treatment at a central waste-water facility.

This installation has eliminated a previous nuisance from heavy oil mist and the daily emission of approximately 5-1/2 tons of hydrocarbons.

Design of Pressure Relief System

The design of a pressure relief system is one of the most important problems in the planning of a refinery or petrochemical plant. The safety of personnel and equipment depends upon the proper design and functioning of this type of system. The consequences of poor design can be disastrous.

A pressure relief system can consist of one relief valve, safety valve, or rupture disc, or of several relief devices manifolded to a common header. Usually the systems are segregated according to the type of material handled, that is, liquid or vapor, as well as to the operating pressures involved.

The several factors that must be considered in designing a pressure relief system are (1) the governing code, such as that of ASME (American Society of Mechanical Engineers, 1962); (2) characteristics of the pressure relief devices; (3) the design pressure of the equipment protected by

the pressure relief devices, (4) line sizes and lengths, and (5) physical properties of the material to be relieved to the system.

In discussing pressure relief systems, the terms commonly used should be defined. The following definitions are taken from the API Manual (1960).

1. A relief valve is an automatic pressure-relieving device actuated by the static pressure upstream of the valve. It opens further with increase of pressure over the set pressure. It is used primarily for liquid service.

2. A safety valve is an automatic relieving device actuated by the static pressure upstream of the valve and characterized by full opening or pop action upon opening. It is used for gas or vapor service.

3. A rupture disc consists of a thin metal diaphragm held between flanges.

4. The maximum allowable working pressure (that is, design pressure), as defined in the construction codes for unfired pressure vessels, depends upon the type of material, its thickness, and the service condition set as the basis for design. The vessel may not be operated above this pressure or its equivalent at any metal temperature higher than that used in its design; consequently, for that metal temperature, it is the highest pressure at which the primary safety or relief valve may be set to open.

5. The operating pressure of a vessel is the pressure, in psig, to which the vessel is usually subjected in service. A processing vessel is usually designed to a maximum allowable working pressure, in psig, that will provide a suitable margin above the operating pressure in order to prevent any undesirable operation of the relief valves. (It is suggested that this margin be approximately 10 percent higher, or 25 psi, whichever is greater.)

6. The set pressure, in psig, is the inlet pressure at which the safety or relief valve is adjusted to open.

7. Accumulation is the pressure increase over the maximum allowable working pressure of the vessel during discharge to the safety or relief valve expressed as a percent of that pressure or pounds per square inch.

8. Over pressure is the pressure increase over the set pressure of the primary relieving device. It is the same as accumulation when the relieving device is set at the maximum allowable working pressure of the vessel. (From this definition note that when the set pressure of the first safety or relief valve to open is less than the maximum allowable working pressure of the vessel the overpressure may be greater than 10 percent of the set pressure of the first safety or relief valve.)

9. Blowdown is the difference between the set pressure and the reseating pressure of a safety or relief valve, expressed as a percent of a set pressure or pounds per square inch.

10. Lift is the rise of the disc in a safety or relief valve.

11. Backpressure is the pressure developed on the discharge side of the safety valves.

12. Superimposed backpressure is the pressure in the discharge header before the safety valve opens (discharged from other valves).

13. Built-up backpressure is the pressure in the discharge header after the safety valve opens.

Safety Valves

Nozzle-type safety valves are available in the conventional or balanced-bellows configurations. These two types of valves are shown schematically in Figures 394 and 395. Backpressure in the piping downstream of the standard-type valve affects its set pressure, but theoretically, this backpressure does not affect the set pressure of the balanced-type valve. Owing, however, to imperfections in manufacture and limitations of practical design, the balanced valves available vary in relieving pressure when the backpressure reaches approximately 40 percent of the set pressure. The actual accumulation depends upon the manufacturer.

Until the advent of balanced valves, the general practice in the industry was to select safety valves that start relieving at the design pressure of the vessel and reach full capacity at 3 to 10 percent above the design pressure. This overpressure was defined as accumulation. With the balanced safety valves, the allowable accumulation can be retained with smaller pipe size.

Each safety valve installation is an individual problem. The required capacity of the valve depends upon the condition producing the overpressure. Some of the conditions that can cause overpressure in refinery process vessels, and the required relief capacity for each condition are given in Table 159.

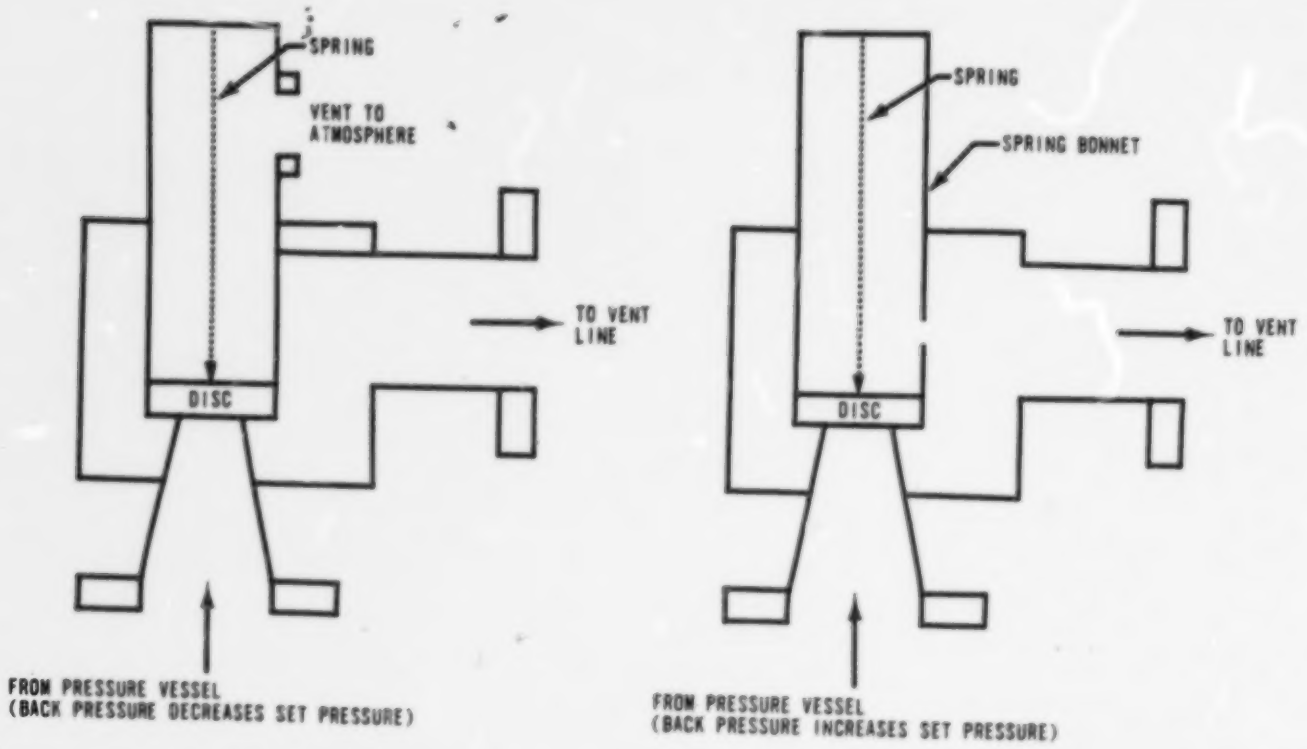


Figure 394. Schematic diagram of standard safety valves (Samans, 1955).

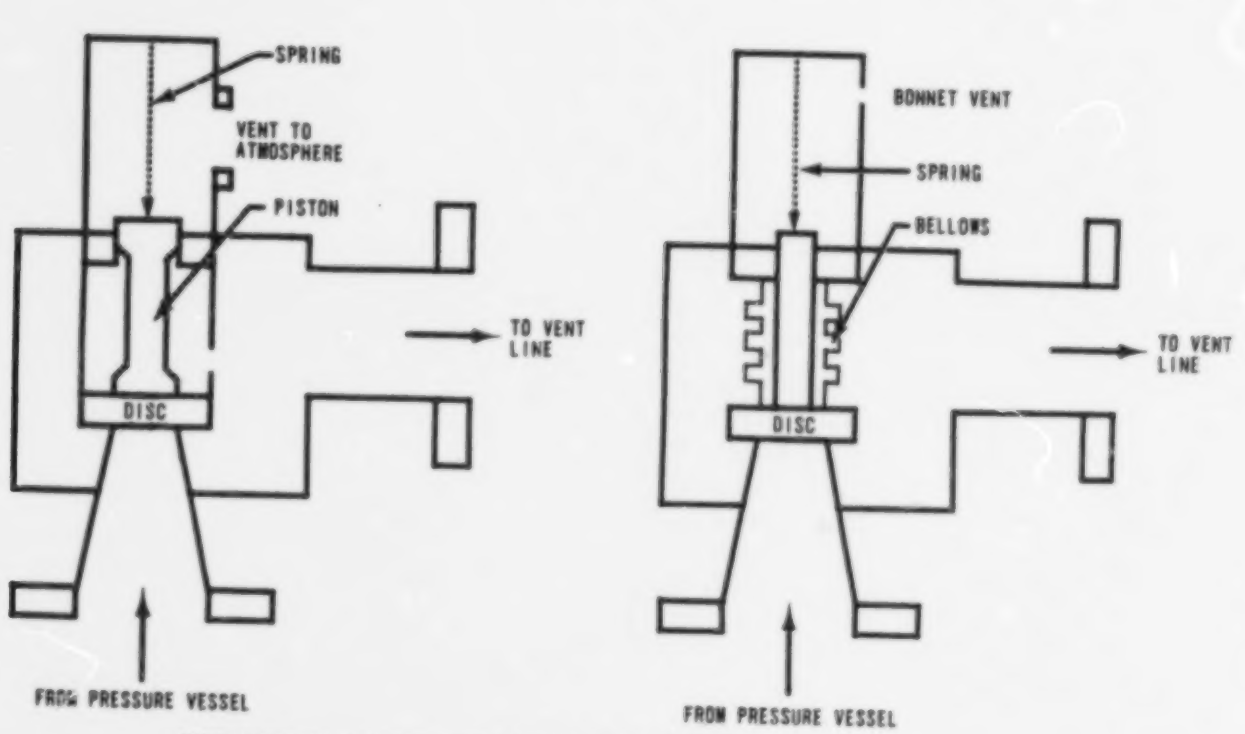


Figure 395. Schematic diagram of balanced safety valves (Samans, 1955)

Rupture Discs

A rupture disc is an emergency relief device consisting of a thin metal diaphragm carefully designed to rupture at a predetermined pressure.

The obvious difference between a relief or safety valve and a rupture disc is that the valve reseats and the disc does not. Rupture discs may be installed in parallel or series with a relief valve. To prevent an incorrect pressure differential

from existing, the space between the disc and the valve must be maintained at atmospheric pressure. The arrangement of a rupture disc to supplement a relief or safety valve is shown in Figure 396. In an installation such as this, the relief or safety valve is sized by conventional methods, presented later, and the rupture disc is usually designed to relieve at 1.5 times the maximum allowable working pressure of the vessel (Bingham, 1958).

Table 159. OPERATIONAL DIFFICULTIES OF A REFINERY AND REQUIRED RELIEF CAPACITIES
(American Petroleum Institute, 1960)

Condition	Required relief capacity	
	Relief valve for liquid relief	Safety relief valve for vapor relief
Closed outlets on vessels	Maximum liquid pump-in rate	Total incoming steam and vapor, plus that generated therein under normal operation
Cooling-water failure to condenser	--	Total incoming steam and vapor, plus that generated therein under normal operation, less vapor condensed by sidestream reflux. Consideration may be given to the suppression of vapor production as the result of the valve's relieving pressure being above operating pressure, with the assumption of constant heat input
Top-tower reflux failure	--	Total vapor to condenser
Sidestream reflux failure	--	Difference between vapor entering and leaving section
Lean-oil failure to absorber	--	None
Accumulation of noncondensables	--	Same effect in towers as for cooling-water failure or overfilling in other vessels
Entrance of highly volatile material:		
Water into hot oil	--	For towers--usually not predictable
Light hydrocarbons into hot oil	--	For heat exchangers--assume an area twice the internal cross-sectional area of one tube so as to provide for the vapor generated by the entrance of the volatile fluid
Overfilling storage or surge vessel	Maximum liquid pump-in rate	
Failure of automatic controls:		
Tower pressure controller, to closed position	--	Total normally uncondensed vapor
All valves, to closed position, except water and reflux valves	No operational requirement	No operational requirement
Abnormal heat or vapor input:		
Fired heaters or steam reboilers	--	Estimated maximum vapor generation including noncondensable from overheating
Split reboiler tube	--	Steam entering from twice the cross-sectional area of one tube
Internal explosions	--	Not controlled by conventional relief devices, but by avoidance of circumstances
Chemical reaction	--	Estimated vapor generation from both normal and uncontrolled conditions
Hydraulic expansion:		
Cold fluid shut in	Nominal size	
Lines outside process area shut in	Nominal size	
Exterior fire	--	Estimate by the method given in Sect 6 of API Manual, RP 520

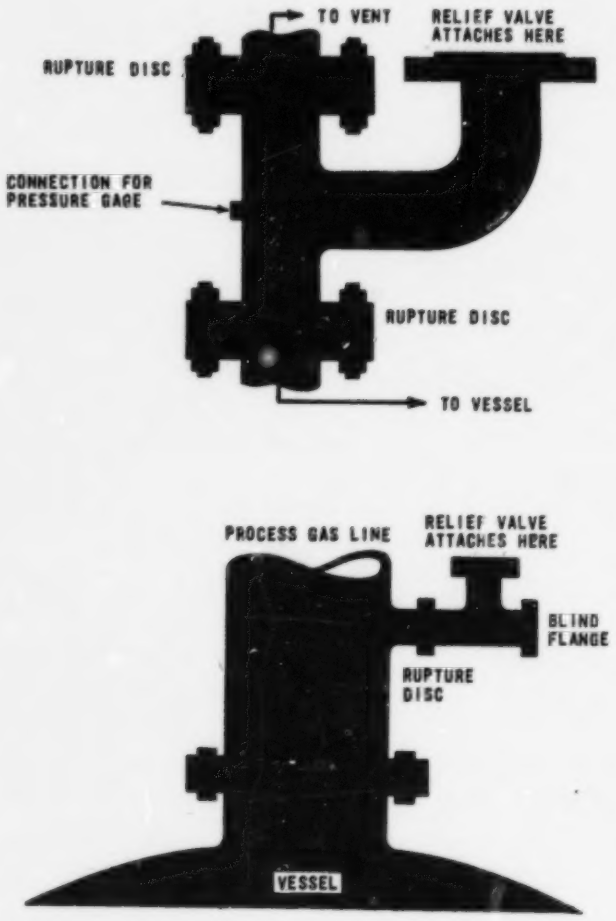


Figure 396. Rupture disc and relief valve installation: (top) How rupture disc gives secondary protection, (bottom) assembly protects relief valve from disc fragments (Bingham, 1958).

In determining the size of a disc, three important effects that must be evaluated are low rupture pressure, elevated temperatures, and corrosion. Minimum rupture pressures with maximum recommended temperatures are given in Table 160. Manufacturers can supply discs that are guaranteed to burst at plus or minus 5 percent of their rated pressures.

The corrosive effects of a system determine the type of material used in a disc. Even a slight amount of corrosion can drastically shorten disc life. Discs are available with plastic linings, or they can be made from pure carbon materials.

Sizing rupture discs

The causes of overpressure, and the required capacity for a disc can be determined by methods previously discussed.

The first estimate of the required rupture disc area can be made by using the formula (Bingham, 1958):

$$A = \frac{Q_a}{11.4\,P} \qquad (108)$$

where

A = area of disc, $in.^2$

Table 160. MINIMUM RUPTURE PRESSURES, psig (Puleo, 1960; Copyrighted by Gulf Publishing Co., Houston, Texas)

Disc size, in.	Aluminum	Aluminum lead lined	Copper	Copper lead lined	Silver	Platinum	Nickel	Monel	Inconel	321 or 347 stainless
1/4	310	405	500	650	485	500	950	1,085	1,550	1,600
1/2	100	160	250	330	250	250	450	530	775	820
1	55	84	120	175	125	140	230	265	410	435
1-1/2	40	60	85	120	85	120	150	180	260	280
2	33	44	50	65	50	65	95	105	150	160
3	23	31	35	50	35	45	63	74	105	115
4	15	21	28	40	28	35	51	58	82	90
6	12	17	25	25	24	26	37	43	61	70
8	9	19	35	35	27	--	30	34	48	55
10	7	16	42	42	--	--	47	28	--	45
12	6	10	55	55	--	--	--	360	--	45
16	5	8	55	55	--	--	--	270	--	33
20	3	8	70	70	--	--	--	215	--	27
24	3	8	60	60	--	--	--	178	--	65
Maximum recommended temperature	250°F 120°F	250°F 120°C	250°F 120°C	250°F 120°C	250°F 120°C	600°F 320°C	750°F 400°C	800°F 430°C	900°F 480°C	600°F 320°C

(base temperature, 72°F [20°C])

Q_a = required capacity, cfm air

P = relieving pressure, psia.

When the overpressure is caused by an explosion, a method of sizing discs has been presented by Lowenstein (1958). In an explosion, a relief or safety valve does not respond fast enough and a rupture disc is required.

The maximum allowable backpressure in an individual discharge line from a disc is 10 percent of the disc's bursting pressure. The maximum allowable backpressure for a manifolded blowdown header serving rupture discs and relief or safety valves should not exceed the individual allowable backpressure for the lowest rupture pressure, or 25 percent of the lowest set pressure of the included valves, whichever is less.

Sizing liquid safety valves

To calculate the required area for a relief valve handling liquid and with constant backpressure, the following formula may be used:

$$A = \frac{Q_l}{C}\left[\frac{S}{P_1 - P_2}\right]^{0.5} \qquad (109)$$

where

A = effective opening of valve, $in.^2$

C = constant for relief valve and percent accumulation

Q_l = required liquid flow at flowing temperature, gpm

P_1 = relieving pressure at inlet, psia

P_2 = discharge pressure at outlet, psia

S = specific gravity of fluid at flowing conditions.

For one manufacturer, the valve constant is 27.2. The overpressure factor for 10 percent accumulation, or overpressure, is determined from Figure 397 to be 0.6. Equation 109 becomes, therefore, for this particular type of valve with a 10 percent accumulation:

$$A = \frac{Q_l}{16.32}\left[\frac{S}{P_1 - P_2}\right]^{0.5} \qquad (110)$$

The use of a balanced relief valve such as the bellows type permits a variable percent backpressure but introduces another variable into the valve-sizing equation. Equation 110 now becomes:

$$A = \frac{Q_l}{16.32\ L_f}\left[\frac{S}{P_1 - P_2}\right]^{0.5} \qquad (111)$$

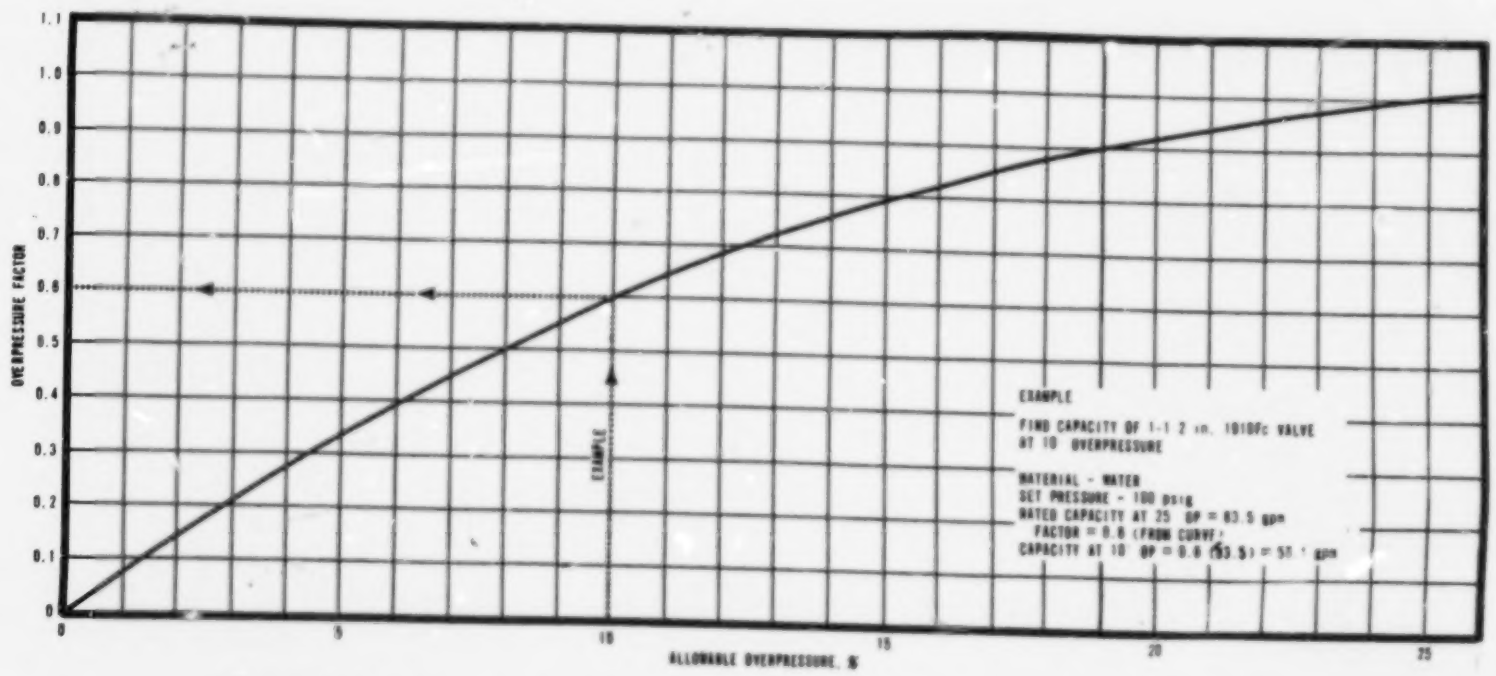


Figure 397. Overpressure sizing factor for liquid relief valves (Consolidated Safety Relief Valves, Manning, Maxwell, and Moore, Inc., Catalog 1900, Tulsa, Okla.).

where nomenclature is as before and L_f is the variable backpressure flow factor. This factor is supplied by the particular manufacturer, typified by Figure 398.

Sizing vapor and gas relief and safety valves

The theoretical area required to vent a given amount of gas or vapor can be calculated by assuming adiabatic reversible flow of an ideal gas through a nozzle. Based upon these assumptions, the following equation can be derived:

$$A = \frac{W}{C\, C_D P_1} \left[\frac{T}{M}\right]^{0.5} \qquad (112)$$

where

A = area, in.^{2}

W = flow capacity, lb/hr

C = nozzle gas constant, which varies as the ratio of specific heats, as shown in Figure 399

C_D = coefficient of discharge for nozzle or orifice

P_1 = inlet pressure, psia

T = inlet temperature, °R

M = average molecular weight of gas.

$$k = c_p/c_v = \frac{\text{specific heat at constant pressure}}{\text{specific heat at constant volume}}$$

For hydrocarbon vapors where the actual value of k is not known, the conservative value of $k = 1.001$ has been commonly used ($C = 315$). The nozzle discharge coefficient for a well-designed relief valve is about 0.97. Hydrocarbon gases can be corrected for nonideality by use of a compressibility factor. With these assumptions, equation 112 reduces to:

$$A = \frac{W}{306\, P_1} \left[\frac{Z\, T}{M}\right]^{0.5} \qquad (113)$$

where

A = area, in.^{2}

Z = compressibility factor. For hydrocarbons, Z may be determined from Figure 400 or is usually taken as 1.0 if unknown.

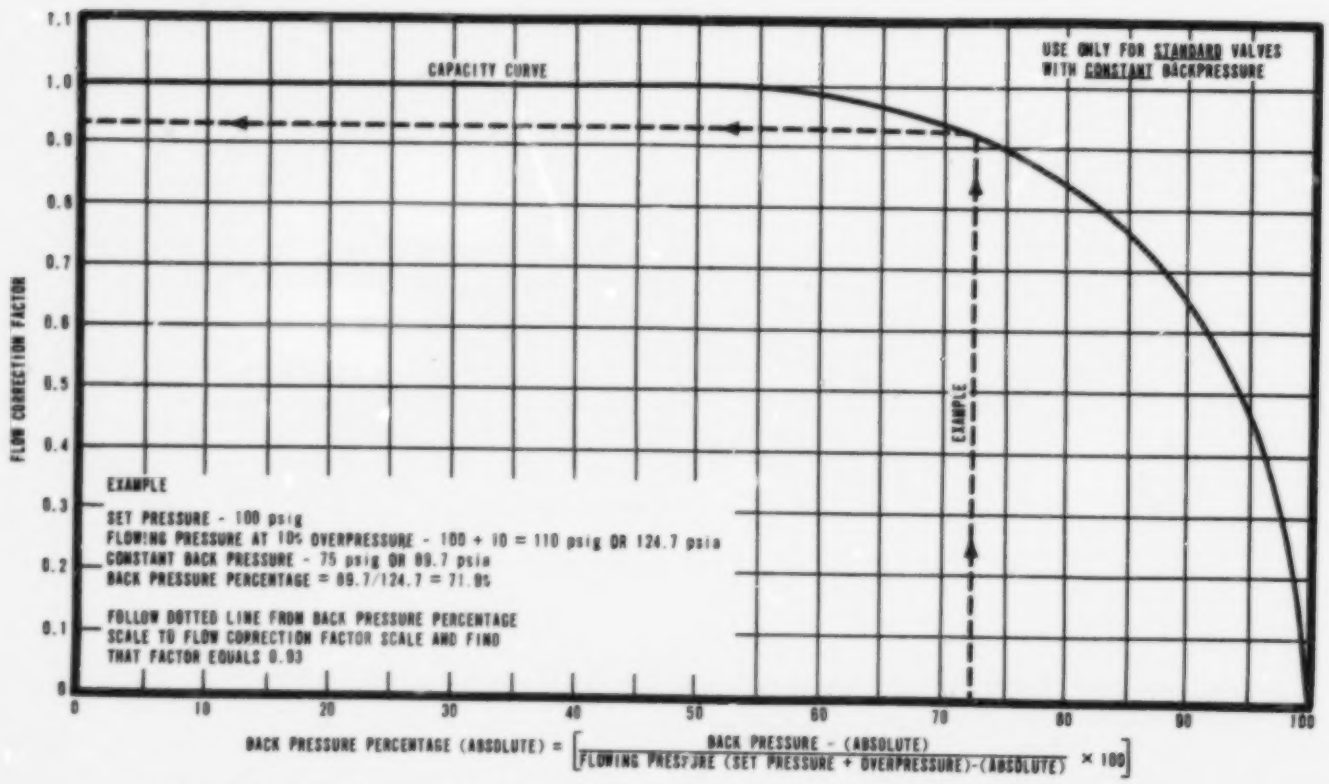


Figure 398. Overpressure sizing factor for standard vapor safety valves (Consolidated Safety Relief Valves, Manning, Maxwell, and Moore, Inc., Tulsa, Okla.).

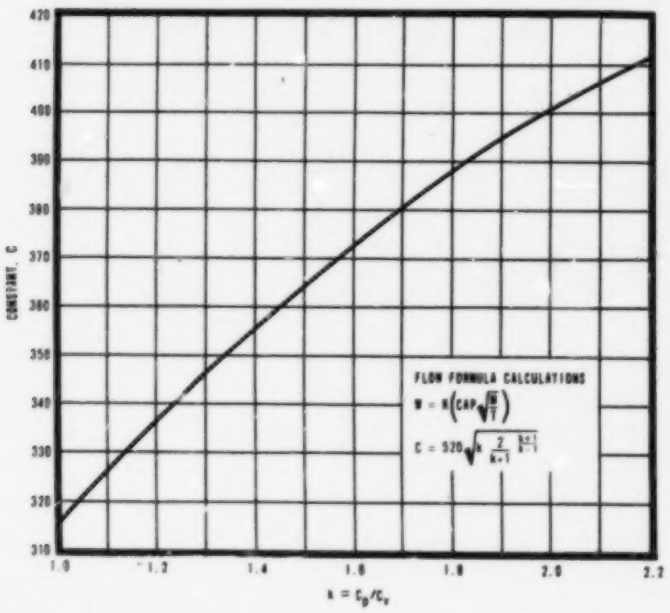


Figure 399. Nozzle gas constant (American Society of Mechanical Engineers, 1962).

Where the critical pressure ratio is such that subsonic fluid velocities are obtained, a correction factor K_{bp} as shown in Figure 401 may be applied. For more precise calculations, the following formula may be used:

$$A = \frac{W}{2,370\ P_1} \left[\frac{ZT/M}{(P_2/P_1)^{1.818} - (P_2/P_1)^{1.909}}\right]^{0.5} \quad (114)$$

An approximation of the absolute temperature at the valve outlet can be calculated under critical flow conditions from the following equation:

$$T_1 = T\left[\frac{2}{k+1}\right] \quad (115)$$

where

T_1 = temperature at valve outlet, °R

T = temperature at valve inlet, °R

k = ratio of specific heats, c_p/c_v.

Before 1957, capacity conversion formulas for valve sizing in petroleum service were given in the API-ASME Code (1951). Since 1957, these formulas have been incorporated in Section VIII of the ASME Unfired Pressure Vessel Code (1962).

The catalogs of relief valve manufacturers are also sources of valve-sizing methods and specific details about various types of valves.

Installing relief and safety valves and rupture discs

The same general rules for discharge piping apply equally to relief and safety valves and rupture discs. Inlet piping should be such that

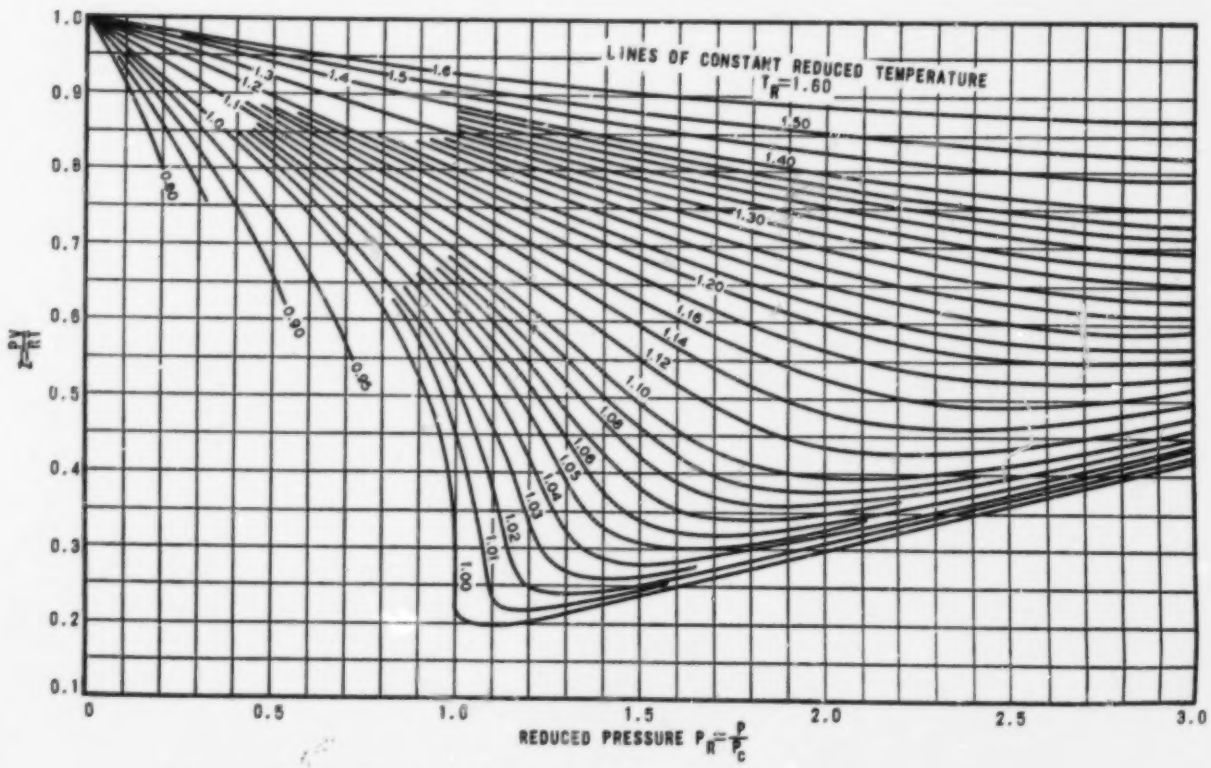


Figure 400. Compressibility constants for hydrocarbons (American Petroleum Institute, 1960).

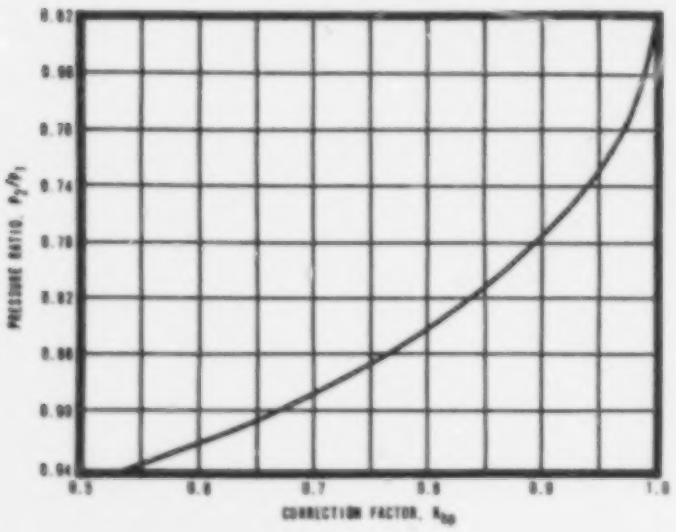


Figure 401. Correction factor (K_{bp}) for subsonic flow (Conison, 1960).

there is direct and unobstructed flow between the vessel and the relief device. A conservative limit for the total pressure drop between the vessel and the safety valve is 2 percent of the absolute relieving pressure.

The discharge piping for relief and safety valves and rupture discs should have a minimum of fittings and bends. There should be minimum loading on the valve, and piping should be used with adequate supports and expansion joints. Suitable drains should be used to prevent liquid accumulation in the piping and valves.

Figures 402, 403, 404, and 405 illustrate good design of relief device piping (for further details on Figures 403 and 405, see Tables 161 and 162, respectively).

Knockout vessels

In a vapor blowdown system, a knockout drum is used to remove entrained liquids from the gas stream. This is particularly important if the gas is to be burned in a smokeless flare. A knockout drum can be quickly sized or checked by the use of a graphical calculation (see Figure 406; Kerns, 1960). The diameter of the drum is based on the allowable vapor velocity, which can be determined by the well-known equation:

$$u_{max} = \phi\left[\frac{\rho_l - \rho_v}{\rho_v}\right]^{0.5} \qquad (116)$$

where

u_{max} = maximum allowable vapor velocity, ft/sec

ρ_l = liquid density, lb/ft^3

ρ_v = vapor density, lb/ft^3

ϕ = a constant. Use ϕ = 0.2 to 0.3. ϕ = 0.227 is often used for light liquid loading.

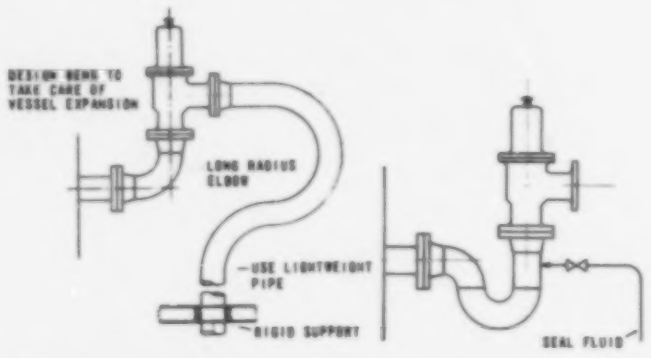


Figure 402. Inlet piping for safety valves; (left) Horizontal vessel nozzles, when used for safety valve mounting can be connected in manner illustrated; (right) valve can be isolated from process fluid in manner illustrated (Driskell, 1960; copyrighted by Gulf Publishing Co., Houston, Texas).

The maximum design velocity should be 0.5 u_{max} to allow for gas surges.

Light liquid loads indicate the use of a vertical vessel, and heavy liquid loads, a horizontal vessel. The optimum dimensions of the vessel will have a length-to-diameter ratio (L/D) of 3 for larger drums and 4 for smaller drums, and never less than 4 feet between tangents (Kerns, 1960).

When wire mesh is used in the drum as an added precaution against mist entrainment, the selected diameter should be multiplied by 0.65 for conventional mesh and 0.62 for high-capacity mesh (Neimeyer, 1961).

Surge time for most designs is 5 to 10 minutes. The graphical sizing method of Figure 406 is based on a surge time of 7-1/2 minutes.

The preliminary sizing of a knockout drum is illustrated by the following example:

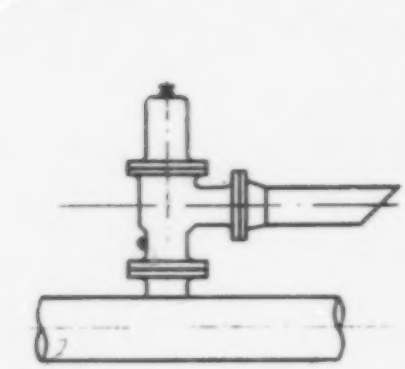
Example 35

Given:

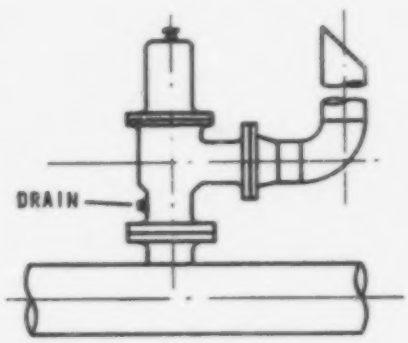
Gas flow 100 ft^3/sec (under flow conditions)

Vapor density, ρ_v, 0.1 lb/ft^3

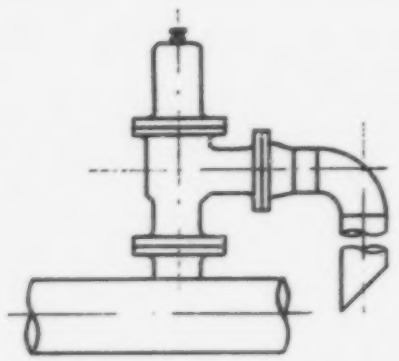
Liquid density, ρ_l, 50 lb/ft^3.



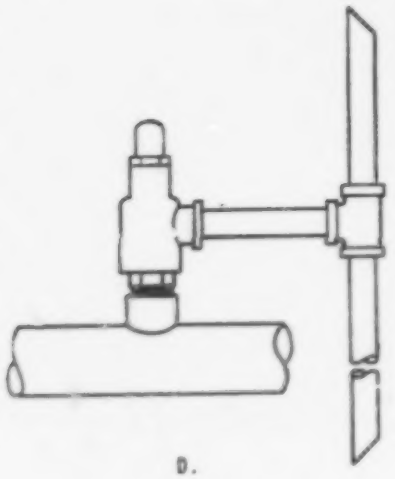
A.



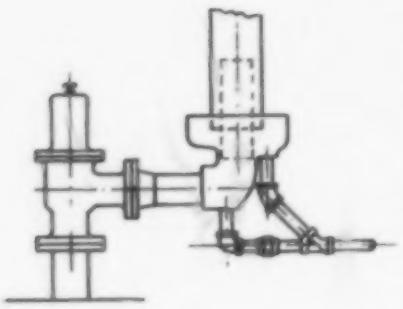
B.



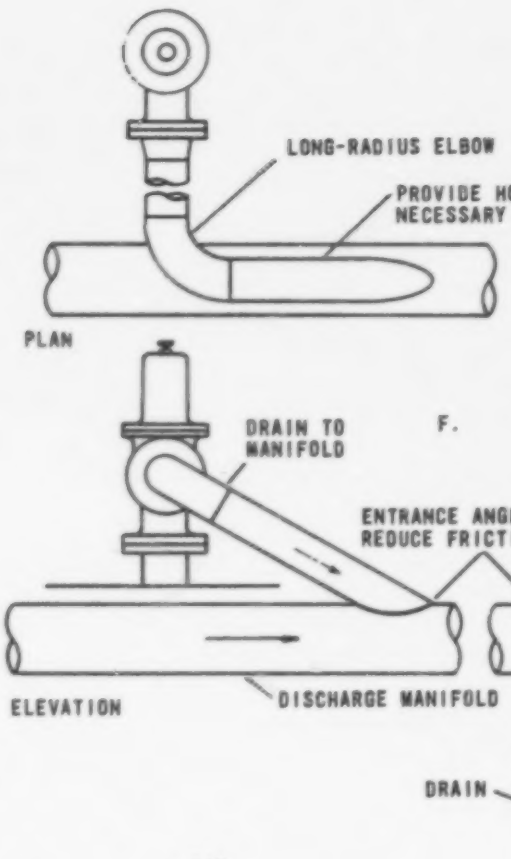
C.

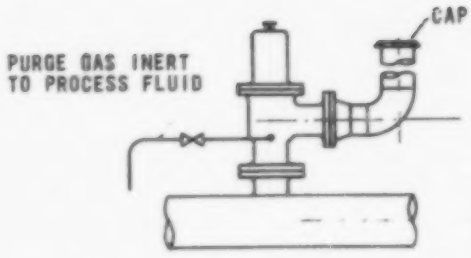


D.



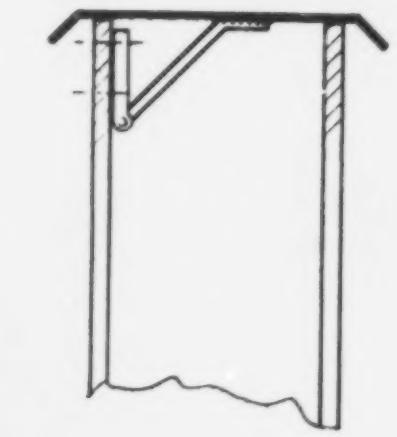
E.





G.

Figure 403. Discharge piping for relief and safety valves: (A) For air or gas service, (B) for air, gas, or steam service, (C) for liquid service, (D) for steam or vapor service, (E) for steam or vapor service to 3-inch pipe, (F) closed system for hazardous service, (G) open system for pyrophoric gases (Driskell, 1960; copyrighted by Gulf Publishing Co., Houston, Texas; for further details, see Table 161).



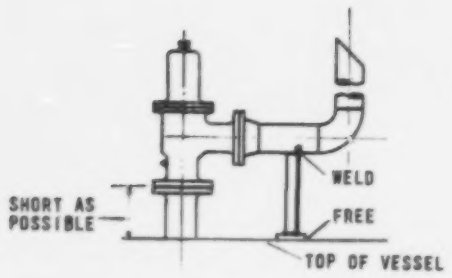


Figure 404. Discharge piping for relief and safety valves: (top) A cap like one illustrated protects discharge pipe from being plugged with snow, (bottom) piping must be adequately anchored to prevent sway ur vibration while the valve is discharging (Driskell, 1960; copyrighted by Gulf Publishing Co., Houston, Texas).

Problem:

Determine dimensions of knockout drum.

Solution:

1. Maximum allowable vapor velocity, u_{max}:

$$u_{max} = \phi \left[\frac{\rho_l - \rho_v}{\rho_v}\right]^{0.5}$$

$$u_{max} = 0.227 \left[\frac{50 - 0.1}{0.1}\right]^{0.5}$$

$$u_{max} = 5.06 \text{ ft/sec.}$$

2. Design vapor velocity, u_D:

$$u_D = u_{max} \times 0.50$$

$$u_D = 5.06 \times 0.50 = 2.5 \text{ ft/sec.}$$

3. Diameter of vessel:

$$D = \left[\frac{(4)(100)}{(\pi)(2.5)}\right]^{0.5}$$

$$D = 7.12 \text{ ft.}$$

Use 7-ft diameter.

4. Height of vessel:

Assume low liquid loading.

Use vertical drum, L/D = 3.

Height = 3 x 7 ft = 21 ft.

Alternative solution:

The same problem can be solved graphically as follows:

1. $\rho_l/\rho_v = \frac{50}{0.1} = 500$

2. Enter Figure 406 at 100 cfs and proceed vertically to

$\rho_l/\rho_v = 500.$

Proceed horizontally and read drum diameter as 7 feet.

3. Again assume L/D ratio = 3.

4. Therefore, drum dimensions are 7 ft in diameter x 21 ft high.

Sizing a blowdown line

As previously stated, the selection of a particular line capacity depends upon the following considerations: (1) Maximum expected vapor flow, (2) maximum allowable backpressure in the system, (3) type of relief device to be used, and (4) governing code.

The maximum design capacity of a blowdown line is generally based upon the operation of a group of relief and safety valves. Selection of a design capacity is based upon upsets in the process or by exterior fire. Table 159 indicates the relief requirements for various conditions.

The maximum allowable backpressure in the relieving system depends upon the vessel with the lowest operating or working pressure, the type of valve used, and the code used. In the past, the pressure drop in the relief manifold was customarily limited to 10 percent of the set

Table 161. SUPPLEMENTARY INFORMATION TO FIGURE 403
(Driskell, 1960; copyrighted by Gulf Publishing Co., Houston, Texas)

Service	Letters keyed to caption for Figure 403	
	Valve indoors	Valve outdoors
Nonhazardous service[a]		
Air or gas	A,[b] B,[b] E	A,[b] B[b]
Liquid	C	C
Steam or vapor		
Discharge pipe size to 1 in.	D	D
Discharge pipe size to 1-1/2 to 2-1/2 in.	B	B
Discharge pipe size to 3 in. and over	E	B
Hazardous service[a]		
Closed system (to vent stack, burning stack, or scrubber)	F	F
Open system (to atmosphere)		
Gas[c]	A, B	A, B
Liquid[d]	C	C
Vapor[c, d]	A, B, D	A, B, D
Pyrophoric gases or vapor[c]	G	G
Low-temperature service		
At or below ambient--design discharge pipe so that snow or ice accumulate at any point in the line where the temperature may be at or below freezing. Use A, if possible. Where necessary, B may be used with a cover.		
Below 32°F--locate safety valve to avoid need for discharge piping, if possible. Discharge opening and exposed spring must be protected from the weather. A housing or local heating may be required. The discharge, if properly designed, may be sealed with a low-viscosity oil and covered with plastic to prevent the entrance of moisture.		

[a]Flammable or toxic fluids are considered hazardous.
[b]Discharge pipe not required if outlet over 7 feet above walkway, or directed away from personnel, or both.
[c]Carry discharge outdoors to a safe elevation.
[d]Carry to an appropriate drain.

pressure. As previously stated, however, the development of balanced relief and safety valves has removed this restriction. In the usual refinery application, there can be considerable savings in piping and valves with balanced valves and about a 40 percent backpressure.

Where several valves discharge to a common header, the use of two separate relieving systems--high- and low-pressure--may be economically advantageous. Otherwise, a single manifold design will be limited by the lowest pressured vessel.

A reduction in the size of the manifold line may be achieved if the operating pressure of a vessel is less than the maximum working, or design, pressure. The set pressure of the relief or safety valve can be made less than the design pressure, permitting a greater backpressure in the relief line.

Another method that can be used with standard safety valves is to plug the guide and vent the bonnet, as shown in Figure 394. An increase in backpressure lowers the relieving pressure and yet does not overpressure the vessel. The arrangement can, however, upset the process if the valve setting is too close to the operating pressure. Thus, in a manifold system, an upset in one section of a process could cause additional relief or safety valves to vent.

In determining the size of a vapor relief line, the pressure drop is usually large, and this precludes the direct use of a Fanning equation. In calculations of compressible fluid flow, the following criteria are used (Crane Company, 1957):

1. If the pressure drop is less than 10 percent of the inlet pressure, reasonable accuracy is obtained if the density of the gas is based upon either inlet or outlet conditions.

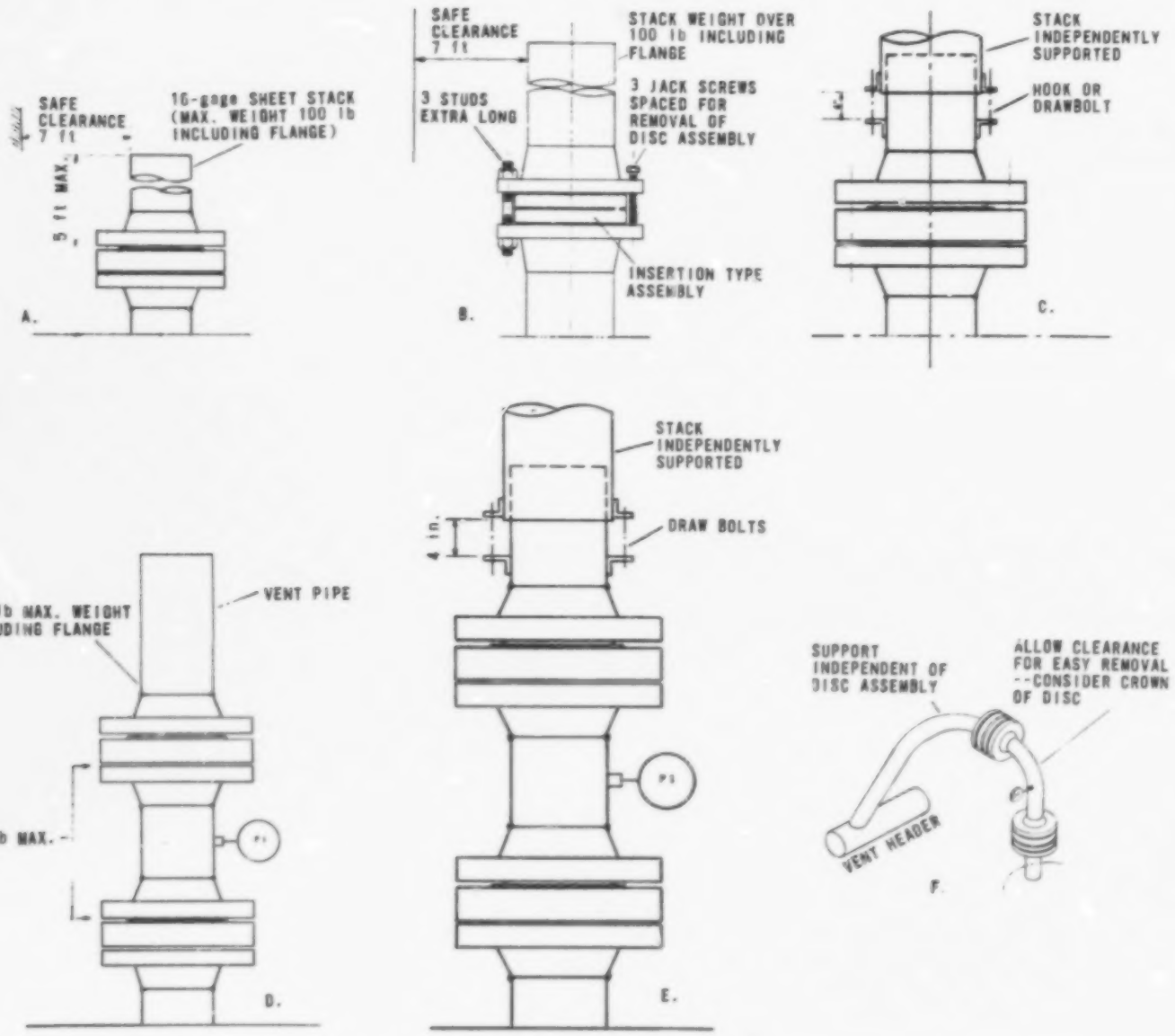


Figure 405. Discharge piping for rupture discs: (A) For lightweight assembly, (B) for heavy assembly with short stack, (C) for heavy assembly with long stack, (D) double disc with lightweight assembly, (E) double disc with heavy assembly, (F) closed system (Driskell, 1960; copyrighted by Gulf Publishing Co., Houston Texas; for further details, see Table 162).

Table 162. SUPPLEMENTARY INFORMATION TO FIGURE 405 (Driskell, 1960; copyrighted by Gulf Publishing Co., Houston, Texas)

Service	Letters keyed to caption for Figure 405	
	Single disc	Double disc
Discharge to atmosphere		
Outdoors, lightweight assembly[a]	A	D
Outdoors, heavy assembly[b]	B, C	E
Indoors[c]	C	E
Closed system	F	F

[a]Parts of assembly 100 lb or less for ease of handling.
[b]Parts of assembly exceed 100 lb and require mechanical lifting.
[c]Vent stack through roof.

2. If the pressure drop is greater than 10 percent but less than about 40 percent of inlet pressure, the Fanning equation may be used with reasonable accuracy if an average density is used. Otherwise a method with a kinetic energy correction can be used.

3. For greater pressure drops, empirical equations can be used.

API Manual RP520 presents kinetic-energy correction factors, as shown in Figure 407, that may be applied to the Fanning equation.

Another method generally used involves dividing the line into increments having pressure drops of

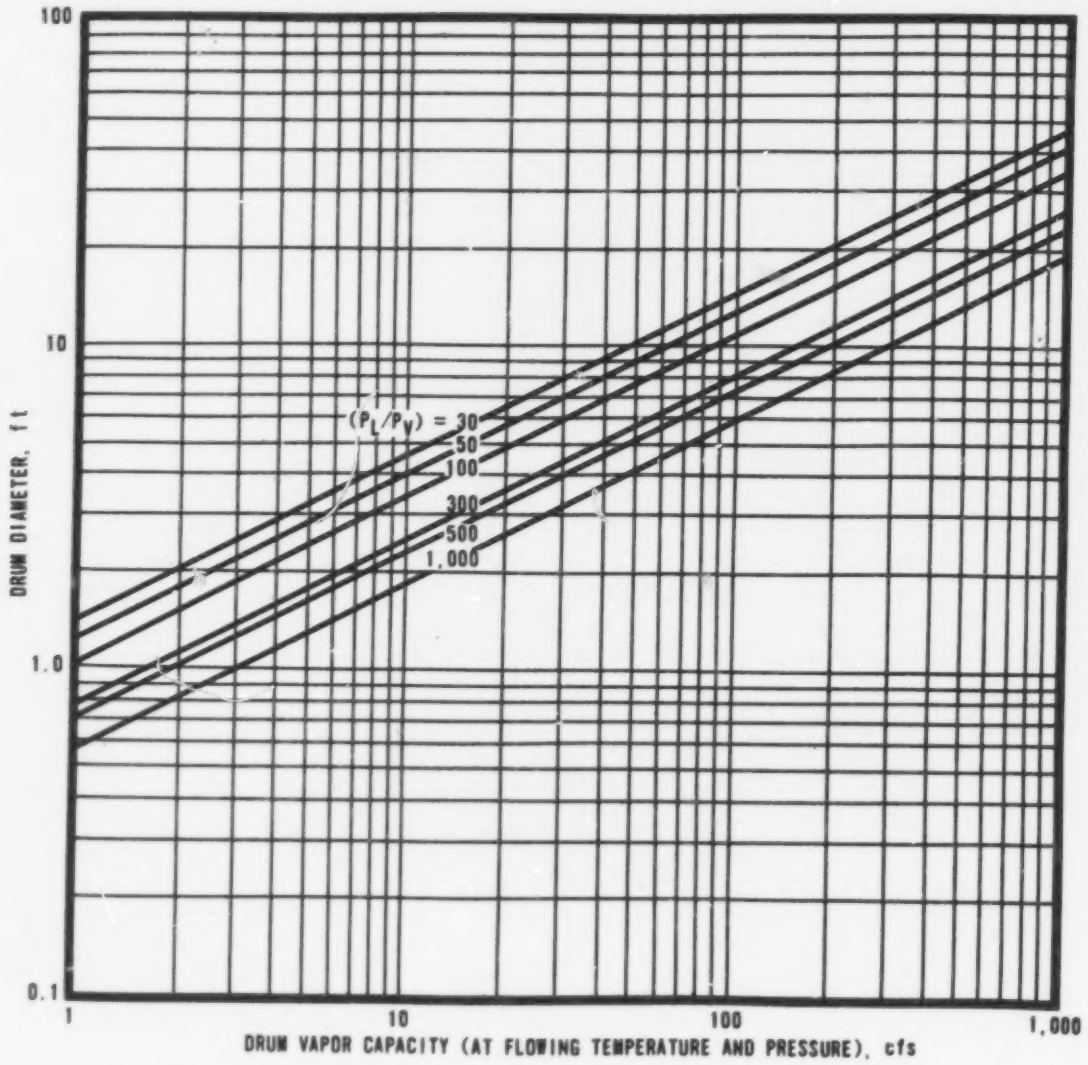


Figure 406. Knockout drum-sizing chart (Kerns, 1960; copyrighted by Gulf Publishing Co., Houston, Texas)

10 percent or less and working from the line terminus back to the relief device.

With the greater availability of computers more exact methods of calculation can be used. Machine computers can handle the tedious equations for calculating pressure drop of compressible fluids where the velocity is subsonic and the density of the vapor or gas is constantly changing.

For hand calculations, a simplified method has been proposed (Conison, 1960) that gives conservative results. The maximum carrying capacity of any line is limited by the acoustic velocity at the outlet of the pipe and in turn sets the outlet pressure. The equation developed by Crocker for solving the maximum pipe capacity for flowing gas and vapors is as follows:

$$P_2 = \frac{W}{d^2} \frac{\sqrt{\frac{RT}{k(k+1)}}}{11,400} \qquad (117)$$

where

P_2 = outlet pressure, psia

d = ID of pipe line, in.

$R = \frac{1,544}{\text{mol wt of gas}}$

k = ratio of specific heats, c_p/c_v

W = vapor or gas, lb/hr

T = outlet temperature, °R.

Equation 117 is used to determine the pressure at the pipe line outlet with W pounds of gas or vapor flowing per hour. If the vapors are discharged to the atmosphere, the outlet pressure must be equal to or greater than atmospheric pressure. If P_2 calculated is less than 1 atmosphere, then W can be increased before any ef-

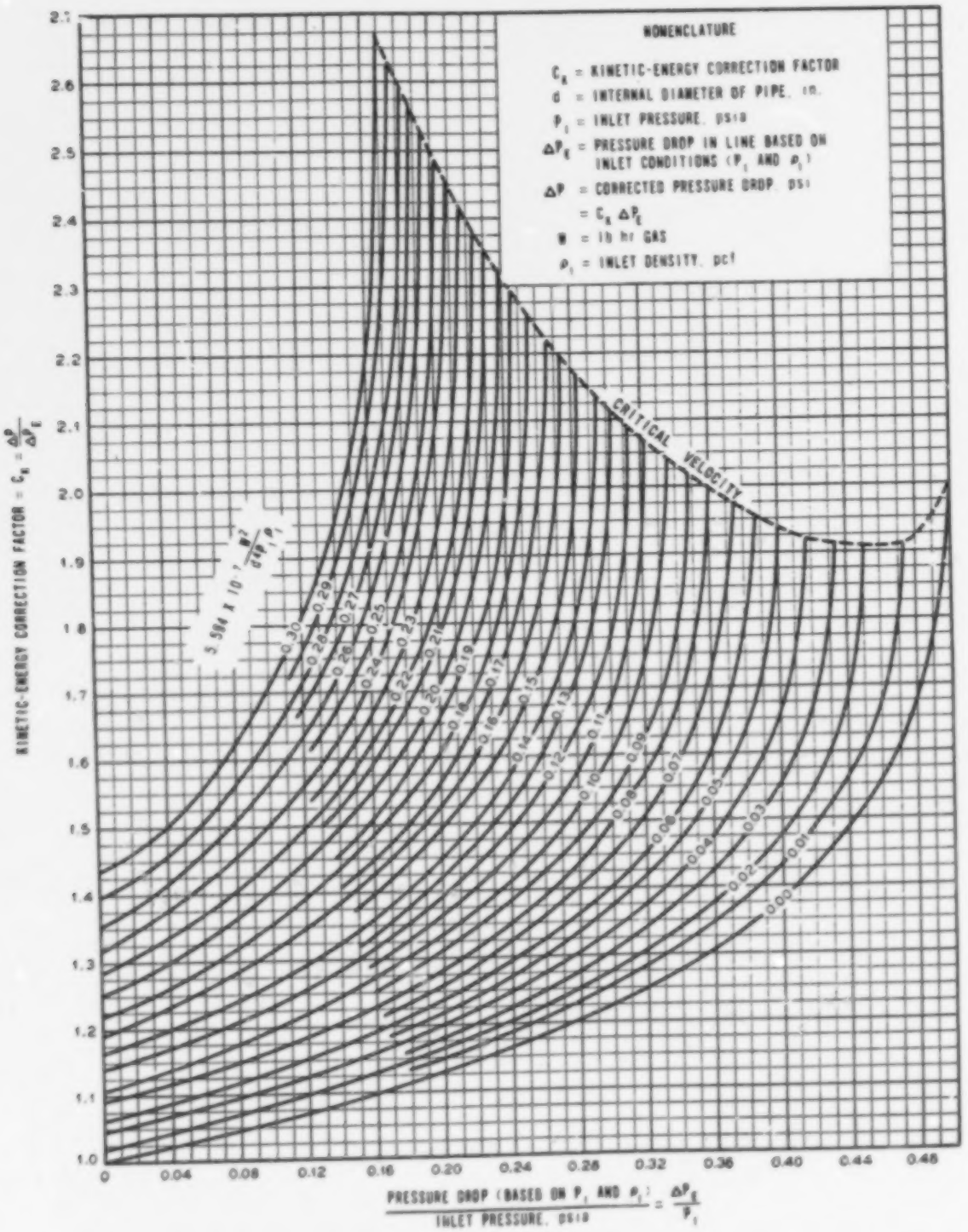

NOMENCLATURE
C_k = KINETIC-ENERGY CORRECTION FACTOR
d = INTERNAL DIAMETER OF PIPE, in.
P_1 = INLET PRESSURE, psig
ΔP_E = PRESSURE DROP IN LINE BASED ON INLET CONDITIONS (P_1 AND ρ_1)
ΔP = CORRECTED PRESSURE DROP, psi
= $C_k \Delta P_E$
W = lb/hr GAS
ρ_1 = INLET DENSITY, pcf
CRITICAL VELOCITY
$5.594 \times 10^{-7} \frac{W^2}{d^4 \rho_1}$
KINETIC-ENERGY CORRECTION FACTOR = $C_k = \frac{\Delta P}{\Delta P_E}$
PRESSURE DROP (BASED ON P_1 AND ρ_1) / INLET PRESSURE, psig = $\frac{\Delta P_E}{P_1}$

Figure 407. Kinetic energy correction for pressure drop for isothermal flow (American Petroleum Institute, 1960).

fect is made on backpressure in the line. If P_2 calculated is equal to atmospheric pressure, then any increase in W increases the discharge pressure at the pipe outlet. If P_2 calculated is greater than atmosphere, then it must be added to the line friction loss calculated from the relief device to the pipe outlet in order to determine the total backpressure at the relief device.

To simplify the calculation of the line pressure drop, the following equation can be used when the line lengths are approximately 100 feet or more or velocity change is small:

$$P_1 = \left[\left(\frac{f\,1\,\rho_{vt}\,\mu_t^2}{2gD\,144}\right)(2\,P_2) + P_2^2\right]^{1/2} \qquad (118)$$

where

P_1 = inlet pressure, psig

P_2 = outlet pressure, psig (equal to values in equation 117 when P_2 = atmospheric pressure or greater)

ρ_{vt} = vapor density, lb/ft^3, at line terminus

f = a friction factor

l = line length, ft

g = 32.2 ft/sec^2

D = line ID, ft

μ_t = velocity at line outlet, fps.

Inspection of equation 118 reveals that the quantity $\left(\frac{f\, l\, \rho_{vt}\, \mu_t^2}{2gD}\right)$ is the Fanning equation for determining pressure drop in a line in pounds per square foot. This quantity is readily determined with the aid of conventional charts in handbooks and other publications.

All gas or vapor terms in the final or line outlet conditions are based on the inlet temperature T, calculated from equation 115 and P_2 from equation 118. Where the line lengths are less than 100 feet, equation 118 is modified as follows:

$$P_1^2 = P_2\left(\frac{f\, l\, \rho_{vt}\, \mu_t^2}{gD}\right) + \left(P_2^2\right) + \left(\frac{2\, \mu_t^2\, \rho_{vt}\, P_2}{g} \log_e \frac{\mu_t}{\mu_i}\right) \qquad (119)$$

where: μ_i = inlet velocity, fps.

Equation 119 can be rearranged to facilitate trial and error solutions:

$$P_1 = \left[P_2^2 + \left(\frac{f\, l}{D} + 2 \log_e \frac{\mu_t}{\mu_i}\right) \frac{\mu_t^2\, P_2\, \rho_{vt}}{g}\right]^{1/2} \qquad (120)$$

The constant-temperature approach provides a safety factor because the line temperature is less than the relief valve outlet temperature. The degree of cooling depends upon atmospheric conditions.

The use of this method of sizing a vapor relief line is illustrated by the following example:

Example 36

Given:

Expected gas flow, 25,000 lb/hr

Outlet temperature at valve, 790°R

Atmospheric pressure, 14.5 psia

Specific volume ($\bar{v}$) at 14.5 psia and 790°R, 13 ft^3/lb

Length of line, 600 equivalent ft

Maximum allowable pressure drop, psia

k of vapor, 1.3

Molecular weight of vapor, 44

Friction factor of gas, 0.017.

Problem:

Select diameter of blowdown line for given conditions.

Solution:

1. Assume a 6-inch ID pipe and calculate terminal pressure P_2:

$$P_2 = \frac{W}{d^2} \frac{\sqrt{\frac{RT}{k\,(k+1)}}}{11,400}$$

$$P_2 = \frac{25,000}{36} \times \frac{\sqrt{\left(\frac{1,544}{44}\right)\left(\frac{790}{1.3\,(1.3+1)}\right)}}{11,400}$$

P_2 = 5.86 psia.

Since P_2 is less than atmospheric pressure, the outlet pressure P_2 equals 14.5 psia.

2. Determine pressure drop in line using equation 120:

$$P_1 = \left[P_2^2 + \left(\frac{f\, l}{D} + 2 \log_e \frac{\mu_t}{\mu_i}\right) \frac{\mu_t^2\, P_2\, \rho_{vt}}{g}\right]^{1/2}$$

$$P_1 = \left[(14.5)^2 + \left(\frac{(0.017)(600)}{0.5} + 2 \log_e \frac{460}{\mu_i}\right) \frac{(460)^2\,(14.5\,(.077)}{(32.2)(144)}\right]^{1/2}$$

$$P_1 = \left[210 + \left(20.4 + 2 \log_e \frac{460}{\mu_i}\right) 50.8\right]^{1/2}$$

As a first approximation, ignore $\log_e \frac{460}{\mu_i}$

Then:

$$P_1 = [210 + (20.4)(50.8)]^{1/2}$$

$$= [1,249]^{1/2}$$

$$= 35.3 \text{ psia.}$$

3. Correct P_1 for change in velocity:

$$\bar{v}_1 = \frac{P_2 \bar{v}_2}{P_1} = \frac{(14.5)(13)}{35.3} = 5.35 \text{ ft}^3/\text{lb}$$

$$\text{Velocity} = \frac{W \bar{v}_1}{A} = \frac{(25,000)(5.35)}{(3,600)(0.2006)}$$

$$\mu_i = 185 \text{ fps}$$

$$50.8 \times 2 \log_e \frac{460}{\mu_i} = 101.6 \log_e \frac{460}{185} =$$

$$101.6 \log_e 2.49 = (101.6)(.912) = 92.6$$

And applying the correction for the log term:

$$P_1 = [1,249 + 92.6]^{1/2} = [1,342]^{1/2}$$

$$P_1 = 36.7 \text{ psia.}$$

THE AIR POLLUTION PROBLEM

The air pollution problem associated with the uncontrolled disposal of waste gases is the venting of large volumes of hydrocarbons and other odorous gases and aerosols. The preferred control method for excess gases and vapors is to recover them in a blowdown recovery system and, failing that, to incinerate them in an elevated-type flare. Such flares introduce the possibility of smoke and other objectionable gases such as carbon monoxide, sulfur dioxide, and nitrogen oxides. Flares have been further developed to ensure that this combustion is smokeless and in some cases nonluminous. Luminosity, while not an air pollution problem, does attract attention to the refinery operation and in certain cases can cause bad public relations. There is also the consideration of military security in which nonluminous emergency gas flares would be desirable.

Smoke From Flares

Smoke is the result of incomplete combustion. Smokeless combustion can be achieved by: (1) Adequate heat values to obtain the minimum theoretical combustion temperatures, (2) adequate combustion air, and (3) adequate mixing of the air and fuel.

An insufficient supply of air results in a smoky flame. Combustion begins around the periphery of the gas stream where the air and fuel mix, and within this flame envelope the supply of air is limited. Hydrocarbon side reactions occur with the production of smoke. In this reducing atmosphere, hydrocarbons crack to elemental hydrogen and carbon, or polymerize to form hydrocarbons. Since the carbon particles are difficult to burn, large volumes of carbon particles appear as smoke upon cooling. Side reactions become more pronounced as molecular weight and unsaturation of the fuel gas increase. Olefins, diolefins, and aromatics characteristically burn with smoky, sooty flames as compared with paraffins and naphthenes (Rupp, 1956).

A smokeless flame can be obtained when an adequate amount of combustion air is mixed sufficiently with the fuel so that it burns completely and rapidly before any side reactions can take place.

Other Air Contaminants From Flares

Combustion of hydrocarbons in the steam-inspirated-type elevated flare appears to be complete. The results of a field test (Sussman et al., 1958) on a flare unit such as this were reported in the form of ratios as follows:

CO_2: hydrocarbons	2,100:1
CO_2: CO	243:1

These results indicate that the hydrocarbon and carbon monoxide emissions from a flare can be much greater than those from a properly operated refinery boiler or furnace. Calculations based on these data, with the assumption of a gas with two carbon atoms and a molecular weight of 30, indicate that the flares in Los Angeles County cause an average daily emission of approximately 100 pounds of hydrocarbons per day and 840 pounds of carbon monoxide per day.

Other combustion contaminants from a flare include nitrogen oxides. The importance of these compounds to the total air pollution problem depends upon the particular conditions in a particular locality. The total emission of nitrogen oxides from the approximately 40 flares in Los Angeles County has been estimated (Chass and George, 1960) at 110 pounds per day.

Other air contaminants that can be emitted from flares depend upon the composition of the gases burned. The most commonly detected emission is sulfur dioxide, resulting from the combustion of various sulfur compounds (usually hydrogen sulfide) in the flared gas. Toxicity, combined with low odor threshold, make venting of hydrogen sulfide to a flare an unsuitable and sometimes dangerous method of disposal. In addition, burning relatively small amounts of hydrogen sulfide can create enough sulfur dioxide to cause crop damage or local nuisance.

Materials that tend to cause health hazards or nuisances should not be disposed of in flares. Compounds such as mercaptans or chlorinated hydrocarbons require special combustion devices with chemical treatment of the gas or its products of combustion.

AIR POLLUTION CONTROL EQUIPMENT

The ideal refinery flare, according to the American Petroleum Institute, is a simple device for safe and inconspicuous disposal of waste gases by combustion. From an air pollution viewpoint, the ideal flare is a combustion device that burns waste gases completely and smokelessly.

Types of Flares

There are, in general, three types of flares for the disposal of waste gases: Elevated flares, ground-level flares, and burning pits.

The burning pits are reserved for extremely large gas flows caused by catastrophic emergencies in which the capacity of the primary smokeless flares is exceeded. Ordinarily, the main gas header to the flare system has a water seal bypass to a burning pit. Excessive pressure in the header blows the water seal and permits the vapors and gases to vent a burning pit where combustion occurs.

The essential parts of a flare are the burner, stack, seal, liquid trap, controls, pilot burner, and ignition system. In some cases, vented gases flow through chemical solutions to receive treatment before combustion. As an example, gases vented from an isomerization unit that may contain small amounts of hydrochloric acid are scrubbed with caustic before being vented to the flare.

Elevated flares

Smokeless combustion can be obtained in an elevated flare by the injection of an inert gas to the combustion zone to provide turbulence and inspirate air. A mechanical air-mixing system would be ideal but is not economical in view of the large volume of gases handled. The most commonly encountered air-inspirating material for an elevated flare is steam. Three main types of steam-injected elevated flares are in use. These types vary in the manner in which the steam is injected into the combustion zone.

In the first type, there is a commercially available multiple nozzle, as shown in Figure 408, which consists of an alloy steel tip mounted on the top of an elevated stack (Brumbaugh, 1947; Hannaman and Etingen, 1956). Steam injection is accomplished by several small jets placed concentrically around the flare tip. These jets

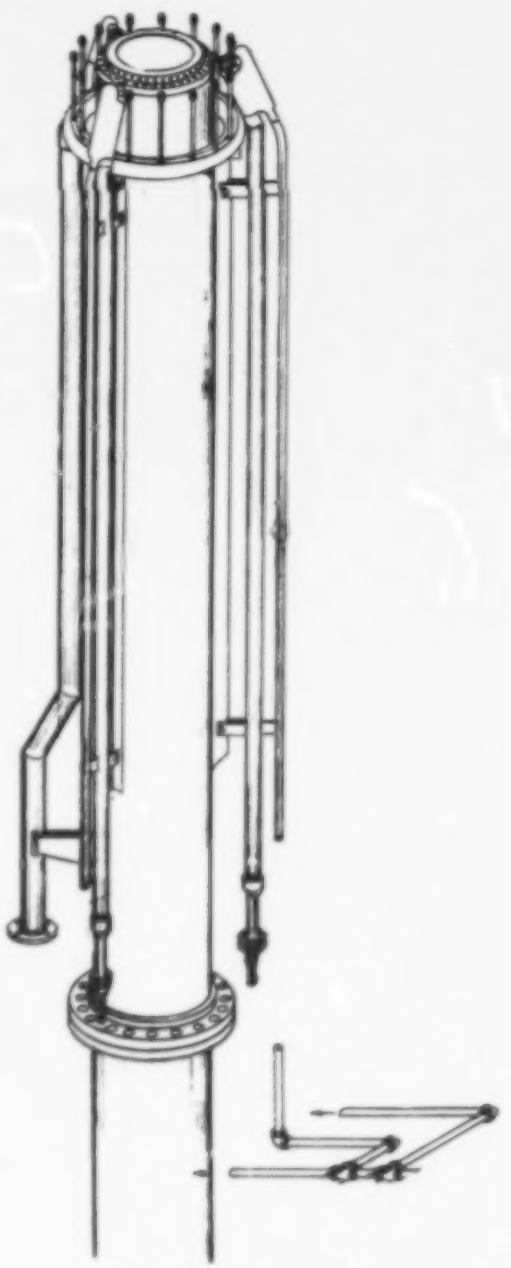


Figure 408. View of John Zink smokeless flare burner (John Zink Co., Tulsa, Okla.)

are installed at an angle, causing the steam to discharge in a converging pattern immediately above the flare tip.

A second type of elevated flare has a flare tip with no obstruction to flow, that is, the flare tip is the same diameter as the stack. The steam is injected by a single nozzle located concentrically within the burner tip. In this type of flare, the steam is premixed with the gas before ignition and discharge.

A third type of elevated flare has been used by the Sinclair Oil Company (Decker, 1950). It is equipped with a flare tip constructed to cause the gases to flow through several tangential openings to promote turbulence. A steam ring at the top of the stack has numerous equally spaced holes about 1/8 inch in diameter for discharging steam into the gas stream.

The injection of steam in this latter flare may be automatically or manually controlled. All the flares of this type located in Los Angeles County are instrumented to the extent that steam is automatically supplied when there is a measurable gas flow. In most cases, the steam is proportioned automatically to the rate of gas flow; however, in some installations, the steam is automatically supplied at maximum rates, and manual throttling of a steam valve is required for adjusting the steam flow to the particular gas flow rate. There are many variations of instrumentation among various flares, some designs being more desirable than others. For economic reasons, all designs attempt to proportion steam flow to the gas flow rate.

Steam injection is generally believed to result in the following benefits: (1) Energy available at relatively low cost can be used to inspirate air and provide turbulence within the flame, (2) steam reacts with the fuel to form oxygenated compounds that burn readily at relatively low temperatures, (3) water-gas reactions also occur with this same end result, and (4) steam reduces the partial pressure of the fuel and retards polymerization. (Inert gases such as nitrogen have also been found effective for this purpose; however, the expense of providing a diluent such as this is prohibitive.)

The effectiveness of steam injection in an elevated flare is graphically illustrated by comparing Figures 409 and 410.

Multisteam-jet-type elevated flare

A multisteam-jet-type elevated flare (Cleveland, 1952) is shown in Figure 411. All relief headers from process units com-

Figure 409. Refinery flare with steam injection in operation.

Figure 410. Refinery flare with steam injection not in operation.

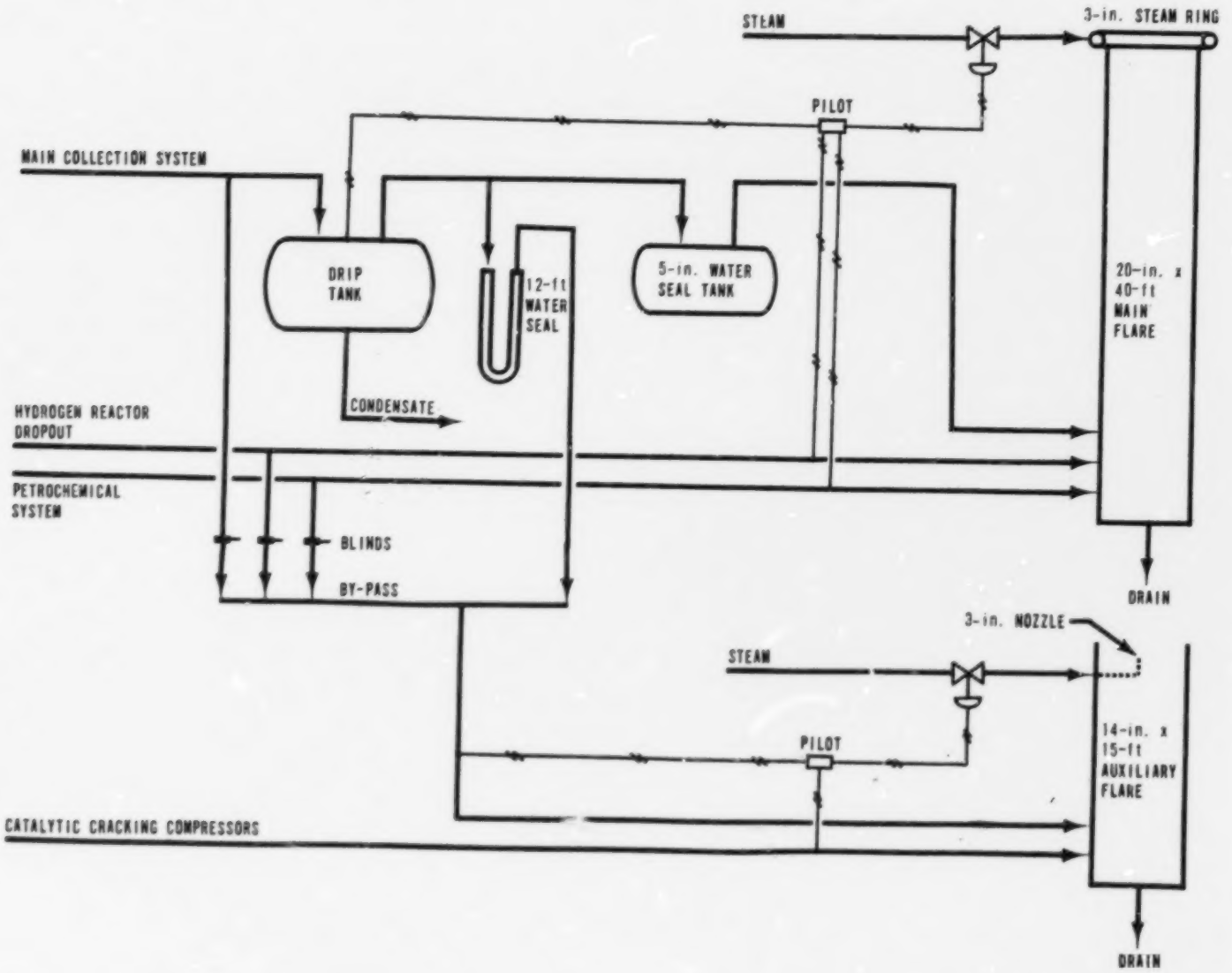


Figure 411. Waste-gas flare system using multiple-steam-jet burner (Cleveland, 1952).

bine into a common header that conducts the hydrocarbon gases and vapors to a large knockout drum. Any entrained liquid is dropped out and pumped to storage. The gases then flow in one of two ways. For emergency gas releases that are smaller than or equal to the design rate, the flow is directed to the main flare stack. Hydrocarbons are ignited by continuous pilot burners, and steam is injected by means of small jet fingers placed concentrically about the stack tip. The steam is injected in proportion to the gas flow. The steam control system consists of a pressure controller, having a range of 0 to 20 inches water column, that senses the pressure in the vent line and sends an air signal to a valve operator mounted on a 2-inch V-Port control valve in the steam line. If the emergency gas flow exceeds the designed capacity of the main flare, backpressure in the vent line increases, displacing the water seal and permitting gas flow to the auxiliary flare. Steam consumption of the burner at a peak flow is about 0.2 to 0.5 pound of steam per pound of gas, depending upon the amount and composition of hydrocarbon gases being vented. In general, the amount of steam required increases with increases in molecular weight and the degree of unsaturation of the gas.

A small amount of steam (300 to 400 pounds per hour) is allowed to flow through the jet fingers at all times. This steam not only permits smokeless combustion of gas flows too small to actuate the steam control valves but also keeps the jet fingers cooled and open.

Esso-type elevated flare

A second type of elevated, smokeless, steam-injected flare is the Esso type. The design is based upon the original installation in the Bayway Refinery of the Standard Oil Company of New Jersey (Smolen, 1951 and 1952). A typical flare system serving a petrochemical plant using this type burner is shown in Figure 412. The type of hydrocarbon gases vented can range from a saturated to a completely unsaturated material. The injection of steam is not only proportioned by the pressure in the blowdown lines but is also regulated according to the type of material being flared. This is accomplished by the use of a ratio relay that is manually controlled. The relay is located in a central control room where the operator has an unobstructed view of the flare tip. In normal operation the relay is set to handle feed gas, which is most common to this installation.

In this installation, a blowdown header conducts the gases to a water seal drum as shown in Figure 413. The end of the blowdown line is equipped with two slotted orifices. The flow transmitter senses the pressure differential across the seal drum and transmits an air signal to the ratio relay. The signal to this relay is either amplified or attenuated, depending upon its setting. An air signal is then transmitted to a flow controller that operates two parallel steam valves. The 1-inch steam valve begins to open at an air pressure of 3 psig and is fully open at 5 psig. The 3-inch valve starts to open at 5 psig and is fully open at 15 psig air pressure. As the gas flow increases, the water level in the pipe becomes lower than the water level in the drum, and more of the slot is uncovered. Thus, the difference in pressure between the line and the seal drum increases. This information is transmitted as an air signal to actuate the steam valves. The slotted orifice senses flows that are too small to be indicated by a Pitot-tube-type flow meter. The water level is maintained 1-1/2 inches above the top of the orifice to take care of sudden surges of gas to the system.

A 3-inch steam nozzle is so positioned within the stack that the expansion of the steam just fills the stack and mixes with the gas to provide smokeless combustion. This type of flare is probably less efficient in the use of steam than some of the commercially available flares but is desirable from the standpoints of simpler construction and lower maintenance costs.

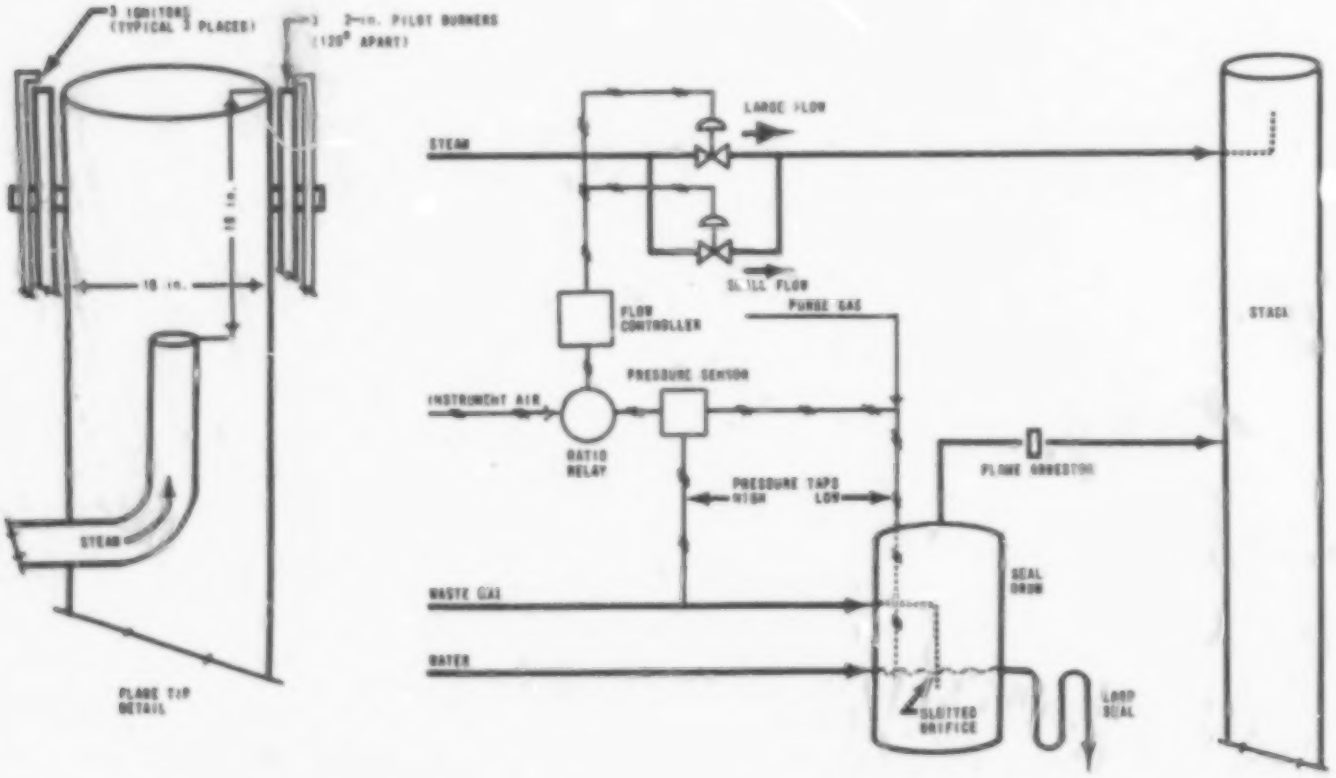


Figure 412. Waste-gas flare system using Esso-type burner.

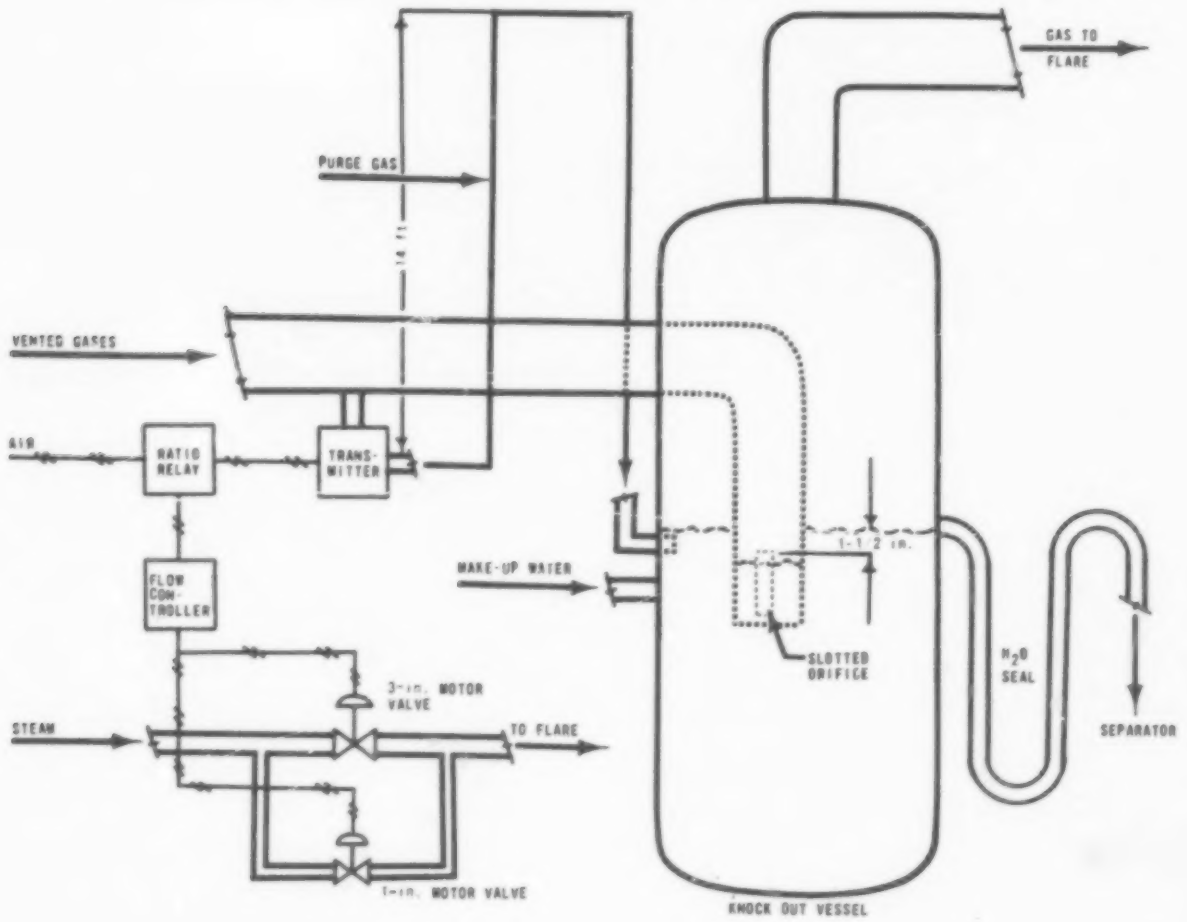


Figure 413. Water seal drum with slotted orifice for measuring gas flow to flare.

Sinclair-type elevated flare

A diagram (Decker, 1950) of an installation using a Sinclair-type elevated flare is shown in Figure 414. A detail of the burner used for this flare is shown in Figure 415.

The flow of steam from the ring inspirates air into the combustion area, and the shroud protects the burner from wind currents and provides a partial mixing chamber for the air and gas. Steam is automatically supplied when there is gas flow. A pressure-sensing element actuates a control valve in the steam supply line. A small bypass valve permits a small, continuous flow of steam to the ring, keeping the steam ring holes open and permitting smokeless burning of small gas flows.

Ground level flares

There are four principal types of ground level flare: Horizontal venturi, water injection, multi-jet, and vertical venturi.

Horizontal, venturi-type ground flare

A typical horizontal, venturi-type ground flare system is shown in Figure 416. In this system, the refinery flare header discharges to a knockout drum where any entrained liquid is separated and pumped to storage. The gas flows to the burner header, which is connected to three separate banks of standard gas burners through automatic valves of the snap-action type that open at predetermined pressures. If any or all of the pressure valves fail, a bypass line with a liquid seal is provided (with no valves in the circuit), which discharges to the largest bank of burners.

The automatic-valve operation schedule is determined by the quantity of gas most likely to be relieved to the system. The allowable back-pressure in the refinery flare header determines the minimum pressure for the control valve on the No. 1 burner bank. On the assumption that the first valve was set at 3 psig, then the second valve for the No. 2 burn-

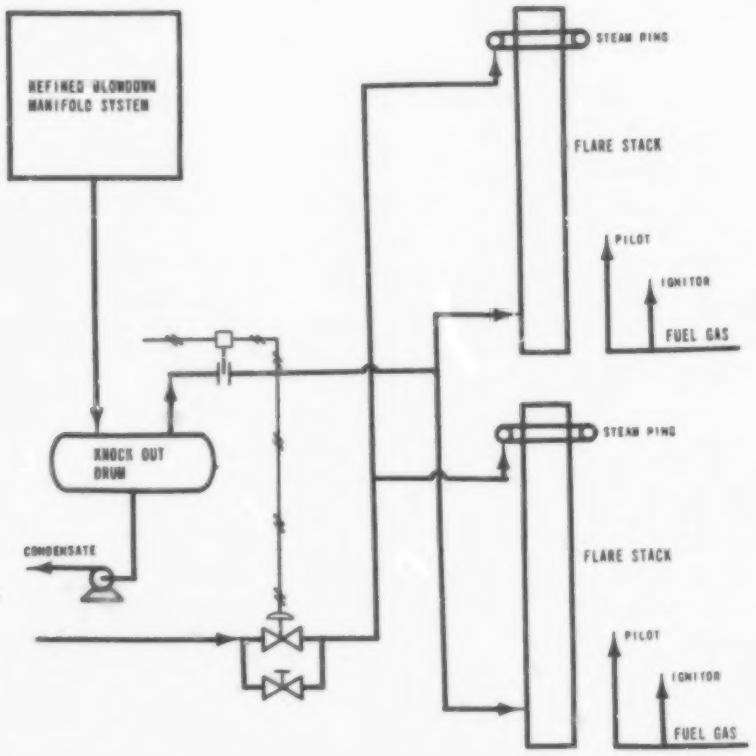


Figure 414. Diagram of waste-gas flare system using a Sinclair burner.

er bank would be set for some higher pressure, say 5 psig. The quantity of gas most likely to be released then determines the size and the number of burners for this section. Again, the third most likely quantity of gas determines the pressure setting and the size of the third control valve. Together, the burner capacity should equal the maximum expected flow rate.

The valve-operating schedule for the system pictured in Figure 416 is set up as follows:

1. When the relief header pressure reaches 3 psig, the first control valve opens and the four small venturi burners go into operation. The controller setting keeps the valve open until the pressure decreases to about 1-1/2 psig.

2. When the header pressure reaches 5 psig, the second valve opens and remains open until the pressure drops to about 3 psig.

3. When the pressure reaches 6 psig, the third valve opens and remains open until the pressure decreases to 4 psig.

4. At about 7 psig, the gas blows the liquid seal.

A small flare unit of this design, with a capacity of 2 million scf per day, reportedly cost

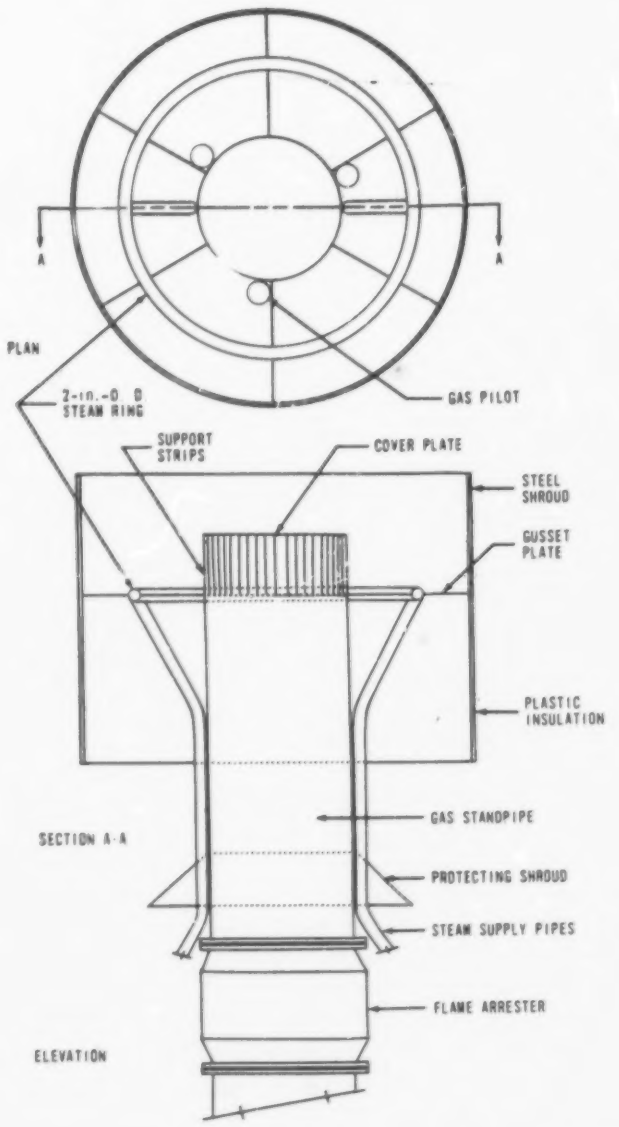


Figure 415. Detail of Sinclair flare burner, plan and elevation (Decker, 1950).

less than $5,000.00 in 1953 (Beychok, 1953). Another large, horizontal, venturi-type flare that has a capacity of 14 million scfh and requires specially constructed venturi burners (throat diameter ranges from 5 to 18 inches) cost $63,000.

Water-injection-type ground flare

Another type of ground flare used in petroleum refineries has a water spray to inspirate air and provide water vapor for the smokeless combustion of gases (Figure 417). This flare requires an adequate supply of water and a reasonable amount of open space.

The structure of the flare consists of three concentric stacks. The combustion chamber contains the burner, the pilot burner, the end of the ignitor tube, and the water spray dis-

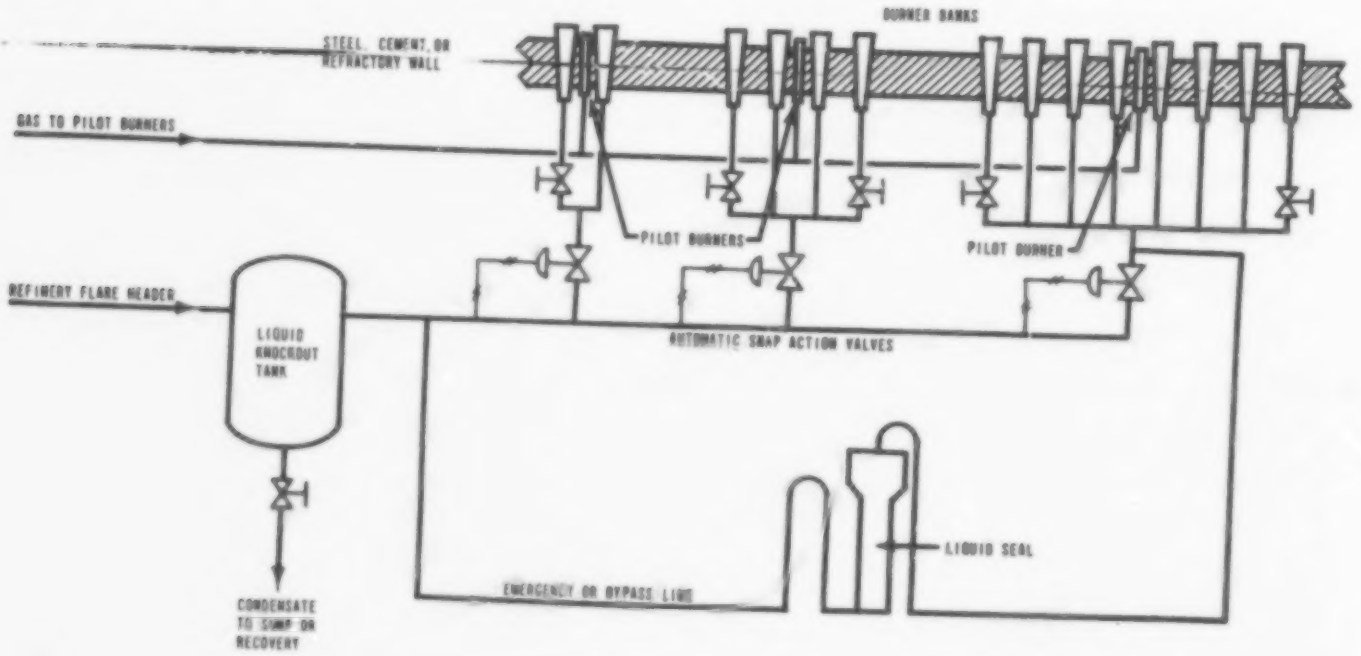


Figure 416. Typical venturi ground flare. The ignitors for pilot burners and the warning element for pilot operation are not shown (American Petroleum Institute, 1957).

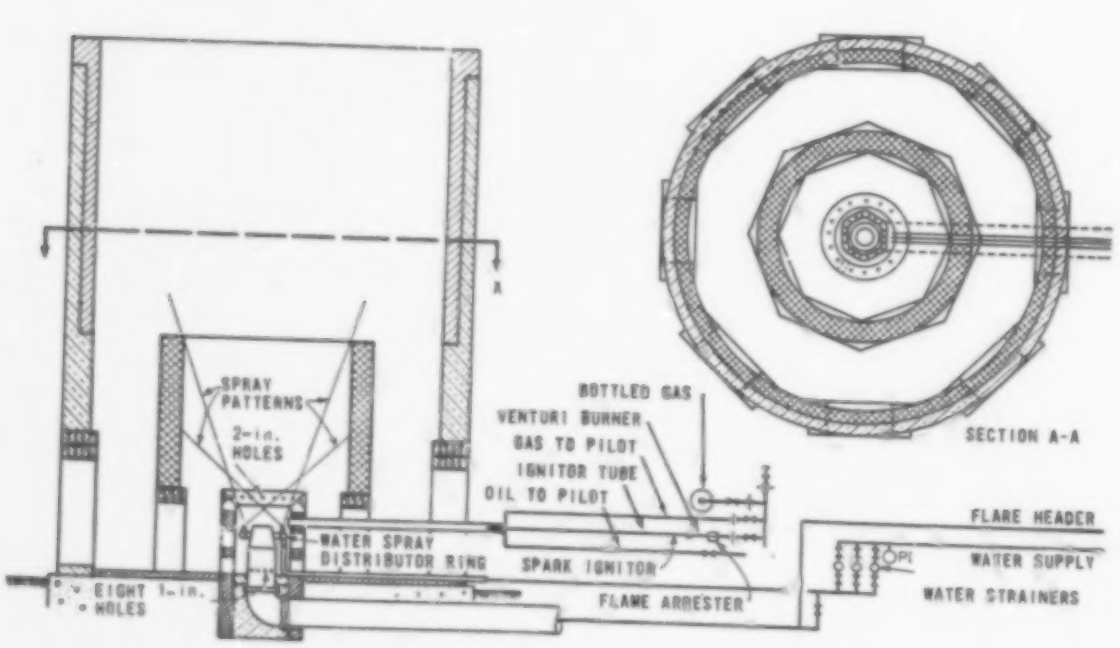


Figure 417. Typical water-spray-type ground flare. Six water sprays are shown. Two pilots and two ignitors are recommended (American Petroleum Institute, 1957).

tributor ring. The primary purpose of the intermediate stack is to confine the water spray so that it will be mixed intimately with burning gases. The outer stack confines the flame and directs it upward.

Water sprays in elevated flares are not too practical for several reasons. Difficulty is experienced in keeping the water spray in the flame zone, and scale formed in the waterline tends to plug the nozzles. In one case it was

necessary to install a return system that permitted continuous waterflow to bypass the spray nozzle. Water main pressure dictates the height to which water can be injected without the use of a booster pump. For a 100- to 250-foot stack, a booster pump would undoubtedly be required. Rain created by the spray from the flare stack is objectionable from the standpoint of corrosion of nearby structures and other equipment.

Water is not as effective as steam for controlling smoke with high gas flow rates, unsaturated materials, or wet gases. The water spray flare is economical when venting rates are not too high and slight smoking can be tolerated. In Los Angeles County, where restrictions on the emission of smoke from flares are very strict, a water spray smokeless flare is not acceptable.

Multijet-type ground flare

A recent type of flare developed by the refining industry is known as a multijet (Miller et al., 1956). This type of flare was designed to burn excess hydrocarbons without smoke, noise, or visible flame. It is claimed to be less expensive than the steam-injected type, on the assumption that new steam facilities must be installed to serve a steam-injected flare unit. Where the steam can be diverted from noncritical operations such as tank heating, the cost of the multijet flare and the steam-inspirating elevated flare may be similar.

A sketch of an installation of a multijet flare is shown in Figure 418. The flare uses two sets of burners; the smaller group handles normal gas leakage and small gas releases, while both burner groups are used at higher flaring rates. This sequential operation is controlled by two water-sealed drums set to release at different pressures. In extreme emergencies, the multijet burners are bypassed by means of a water seal that directs the gases to the center of the stack. This seal blows at flaring rates higher than the design capacity of the flare. At such an excessive rate, the combustion is both luminous and smoky, but the unit is usually sized so that an overcapacity flow would be a rare occurrence. The overcapacity line may also be designed to discharge through a water seal to a nearby elevated flare rather than to the center of a multijet stack. Similar staging could be accomplished with automatic valves or backpressure regulators; however, in this

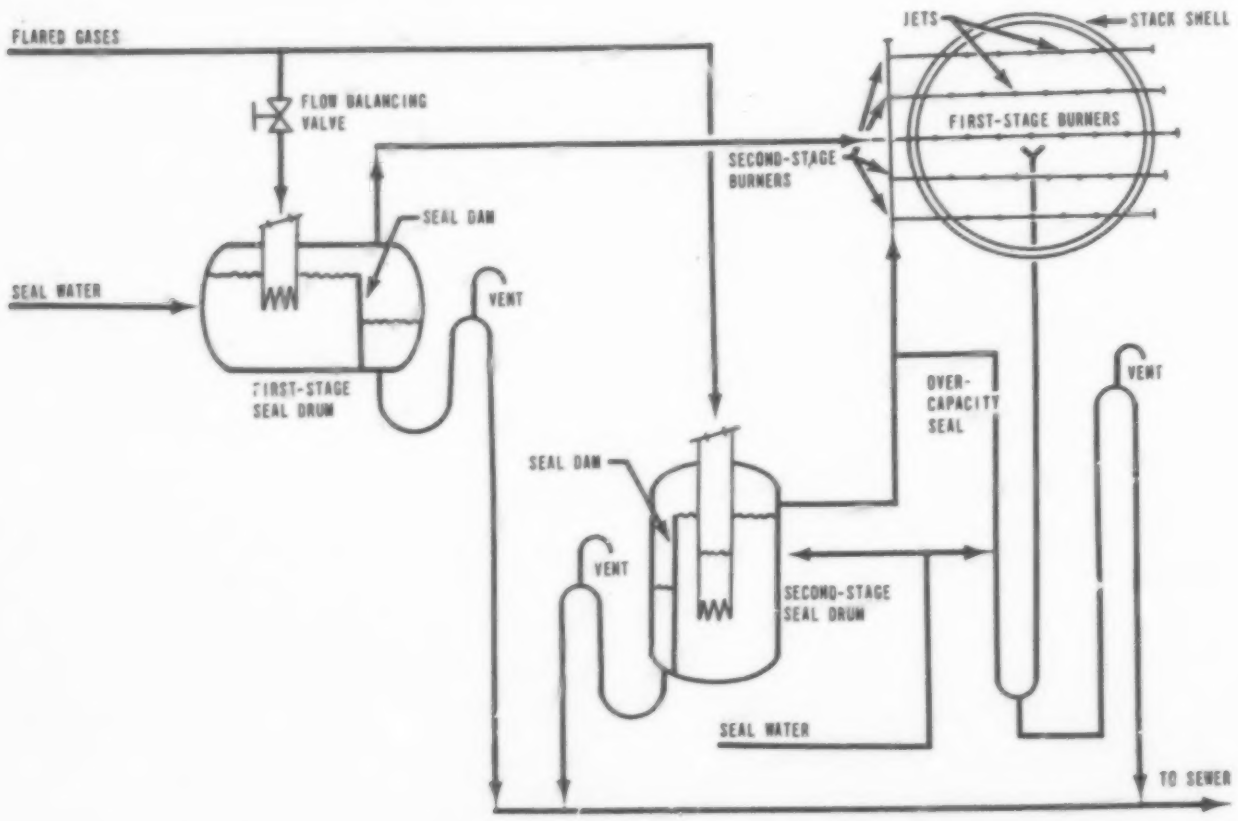


Figure 418. Flow diagram of multijet-flare system (Miller et al., 1956).

case, the water seal drums are used because of reliability and ease of maintenance. The staging system is balanced by adjusting the hand control butterfly valve leading to the first-stage drum. After its initial setting, this valve is locked into position.

Design details of this installation are given in the literature reference (Miller et al., 1956).

Vertical, venturi-type ground flare

Another type of flare based upon the use of commercial-type venturi burners is shown in Figure 419. This type of flare has been used to handle vapors from gas-blanketed tanks, and vapors displaced from the depressuring of butane and propane tank trucks. Since the commercial venturi burner requires a certain minimum pressure to operate efficiently, a gas blower must be provided. In the installation shown in Figure 420, two burners operate at a pressure of 1/2 to 8 psig. A compressor takes vapors from tankage and discharges them at a rate of 6,000 cfh and 7 psig through a water seal tank and a flame arrestor to the flare. This type of arrangement can readily be modified to handle different volumes of vapors by the installation of the necessary number of burners.

This type of flare is suitable for relatively small flows of gas of a constant rate. Its main application is in situations where other means of disposing of gases and vapors are not available.

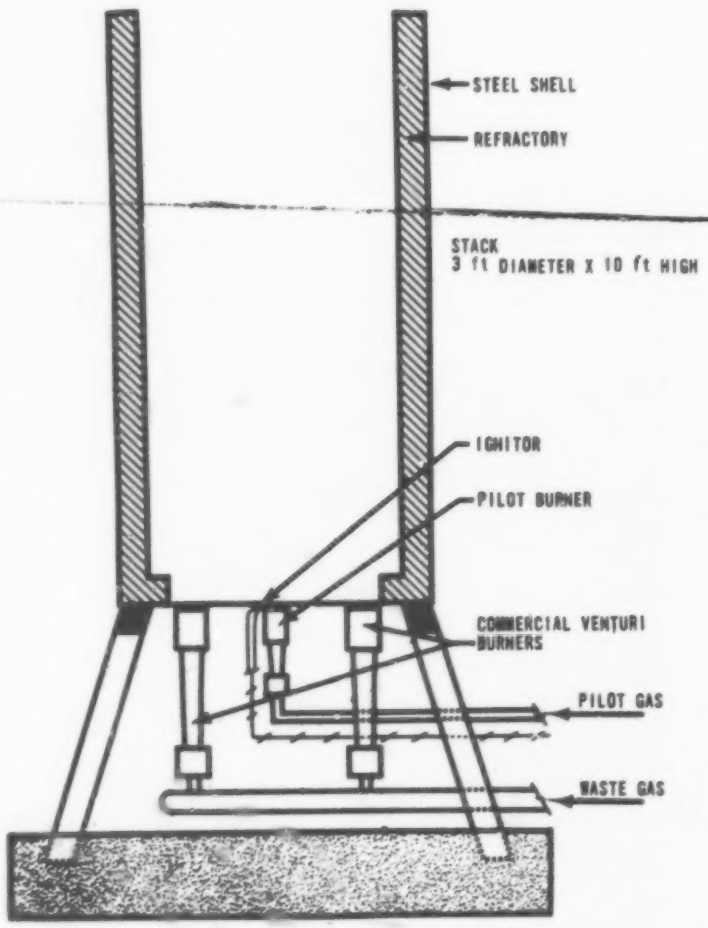


Figure 419. Vertical, venturi-type flare.

Effect of steam injection

A flare installation that does not inspirate an adequate amount of air or does not mix the air and hydrocarbons properly emits dense, black clouds of smoke that obscure the flame. The injection of steam into the zone of combustion causes a gradual decrease in the amount of smoke, and the flame becomes more visible. When trailing smoke has been eliminated, the flame is very luminous and orange with a few wisps of black smoke around the periphery. The minimum amount of steam required produces a yellowish-orange, luminous flame with no smoke. Increasing the amount of steam injection further decreases the luminosity of the flame. As the steam rate increases, the flame becomes colorless and finally invisible during the day. At night this flame appears blue.

An injection of an excessive amount of steam causes the flame to disappear completely and be replaced with a steam plume. An excessive amount of steam may extinguish the burning gases and permit unburned hydrocarbons to discharge to the atmosphere. When the flame is out, there is a change in the sound of the flare because a steam hiss replaces the roar of combustion. The commercially available pilot burners are usually not extinguished by excessive amounts of steam, and the flame reappears as the steam injection rate is reduced. As the use of automatic instrumentation becomes more prevalent in flare installations, the use of excessive amounts of steam and the emission of unburned hydrocarbons decrease and greater steam economies can be achieved. In evaluating flare installations from an air pollution standpoint, controlling the volume of steam is important. Too little steam results in black smoke, which, obviously, is objectionable. Conversely, excessive use of steam produces a white steam plume and an invisible emission of unburned hydrocarbons. A condition such as this can also be a serious air pollution problem.

Design of a smokeless flare

The choice of a flare is dictated by the particular requirements of the installation. A flare may be

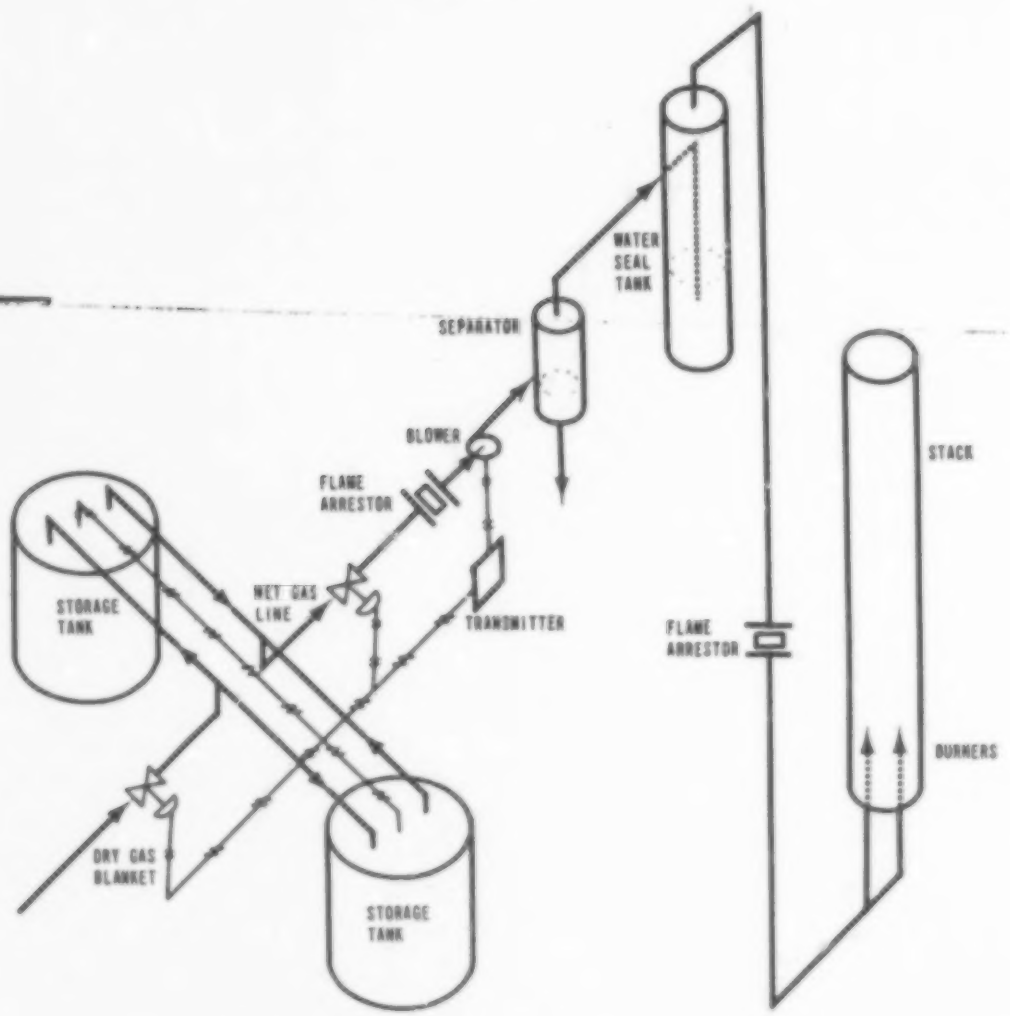


Figure 420. Flow diagram of tank-gas-blanketing system venting to a vertical, venturi flare.

located either at ground level or on an elevated structure. Ground flares are less expensive, but locations must be based upon considerations such as proximity of combustible materials, tanks, and refinery processing equipment. In a congested refinery area, there may be no choice but to use an elevated flare.

A method of determining the distance a stack should be from surrounding equipment and personnel has been developed (Hajek and Ludwig, 1960). The recommended equation is

$$D = \sqrt{\frac{(F)(H)}{(4)(3.14)(K)}} \qquad (121)$$

where

D = minimum distance, ft from the flame to the object

F = a dimensionless constant equal to 0.20 for methane, which has a hydrogen-to-carbon weight ratio of 0.333, and equal to 0.33 for propane, which has a hydrogen-to-carbon weight ratio of 0.222. (Use 0.40 when in doubt.)

H = heat release, Btu/hr

K = a constant, Btu/hr-ft^2:

K = 1,000 for objects exposed 20 minutes of more

K = 1,500 for objects exposed less than 20 minutes.

The usual flare system includes gas collection equipment, the liquid knockout tank preceding the flare stack. A water seal tank is usually located between the knockout pot and the flare stack to prevent flashbacks into the system. Flame arrestors are sometimes used in place of or in conjunction with a water seal pot. Pressure-temperature-actuated check valves have been used in small ground flares to prevent flash-back. The

flare stack should be continuously purged with steam or refinery gas to prevent the formation of a combustible mixture that could cause an explosion in the stack. A purge steam flow of 10 cfm is recommended for a commercial-size burner section (Hajek and Ludwig, 1960).

The preferred method of inspirating air is injecting steam either into the stack or into the combustion zone. Water has sometimes been used in ground flares where there is an abundant supply. There is, however, less assurance of complete combustion when water is used, because the flare is limited in its operation by the type and composition of gases it can handle efficiently.

The diameter of the flare stack depends upon the expected emergency gas flow rate and the permissible backpressure in the vapor relief manifold system. The stack diameter is usually the same or greater than that of the vapor header discharging to the stack and should be the same diameter as or greater than that of the burner section. The velocity of the gas in the stack should be as high as possible to permit use of lower stack heights, promote turbulent flow with resultant improved combustion, and prevent flashback. Stack gas velocity is limited to about 500 fps in order to prevent extinction of the flame by blowout. A discharge velocity of 300 to 400 fps based upon pressure drop considerations is the optimum design figure of a patented flare tip manufactured by the John Zink Company. The nature of the gas determines optimum discharge velocity (John Zink Company).

Adequate stack heights must be provided to permit safe dispersion of toxic or combustible material in the event of pilot burner failure. Techniques are available for calculating adequate stack heights to obtain certain ground concentrations at various distances from the stack, depending upon atmospheric conditions (Bodurtha, 1958; Gosline et al., 1956). These methods of calculation should not be generally applied to any one location, and meteorological data should be obtained for the particular location involved.

The structural support of an elevated-flare stack over 40 to 50 feet high requires the use of guy wires. A self-supporting stack over 50 feet high requires a large and expensive foundation. Stacks over 100 feet high are usually supported by a steel structure such as is shown in Figure 421.

Three burner designs for elevated flares have been discussed--the multisteam-jet, or Zink, and the Esso and Sinclair types. The choice of burner is a matter of personal preference. The Zink burner provides more efficient use of steam, which is important in a flare that is in constant use. On the other hand, the simplicity, ease of

Figure 421. A 200-ft flare stack supported by a steel tower (Atlantic-Richfield Co., Wilmington, Calif.).

maintenance, and large capacity of the Esso burner might be important considerations in another installation.

As previously mentioned, the amount of steam required for smokeless combustion varies according to the maximum expected gas flow, the molecular weight, and the percent of unsaturated hydrocarbons in the gas. Data for steam requirements for elevated flares are shown in Figure 422. Actual tests should be run on the various materials to be flared in order to determine a suitable steam-to-hydrocarbon ratio. In the typical refinery, the ratio of steam to hydrocarbon varies from 0.2 to 0.5 pound of steam per pound of hydrocarbon. The John Zink Company's recommendation for their burner is 5 to 6 pounds per 1,000 cubic feet of a 30-molecular-weight gas at a pressure drop of 0.65 psig.

Pilot ignition system

The ignition of flare gases is normally accomplished with one of three pilot burners. A sepa-

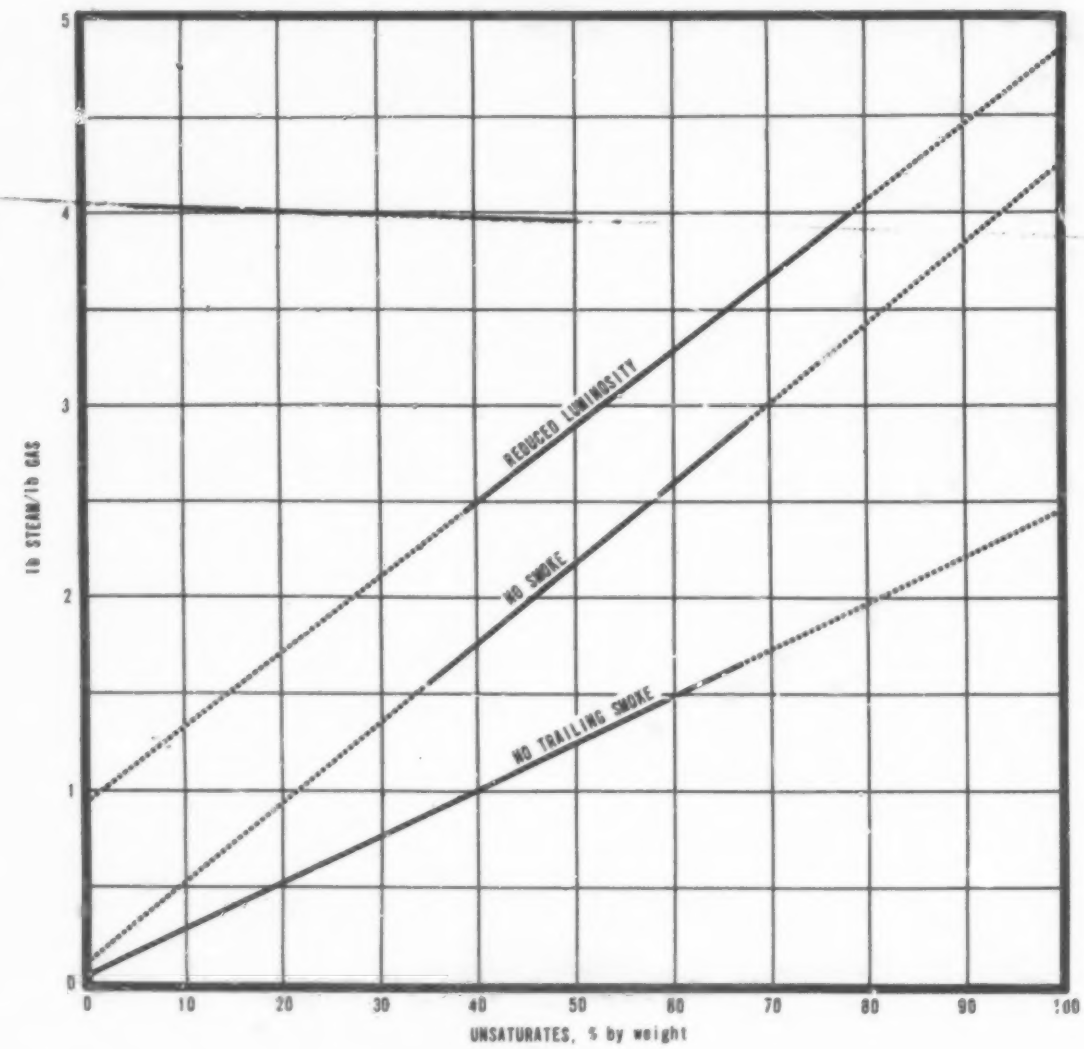


Figure 422. Steam requirements for smokeless burning of unsaturated hydrocarbon vapor (American Petroleum Institute, 1957).

rate system must be provided for the ignition of the pilot burner to safeguard against flame failure. In this system, an easily ignited flame with stable combustion and low fuel usage must be provided. In addition, the system must be protected from the weather.

One good arrangement for a pilot ignitor is shown in Figure 423. To obtain the proper fuel-air ratio for ignition in this system, the two plug valves are opened and adjustments are made with the globe valves, or pressure regulator valves. After the mixing, the fuel-air mixture is lit in an ignition chamber by an automotive spark plug controlled by a momentary-contact switch. The ignition chamber is equipped with a heavy Pyrex glass window through which both the spark and ignition flame can be observed. The flame front travels through the ignitor pipe to the top of the pilot burner. The mixing of fuel gas and air in the supply lines is prevented by the use of double check valves in both the fuel and air line. The collection of water in the ignitor tube can be prevented by the installation of an automatic drain in the lower end of the tube at the base of the flare. After the pilot burner has beer lit, the flame front generator is turned off by closing the plug cocks in the fuel and air lines. This prevents the collection of condensate and the overheating of the ignitor tube.

On elevated flares, the pilot flame is usually not visible, and an alarm system to indicate flame failure is desirable. This is usually accomplished by installing thermocouples in the pilot burner flame. In the event of flame failure, the temperature drops to a preset level, and an alarm sounds.

Instrumentation and control of steam and gas

For adequate prevention of smoke emission and possible violations of air pollution regula tions, an elevated, smokeless flare should be

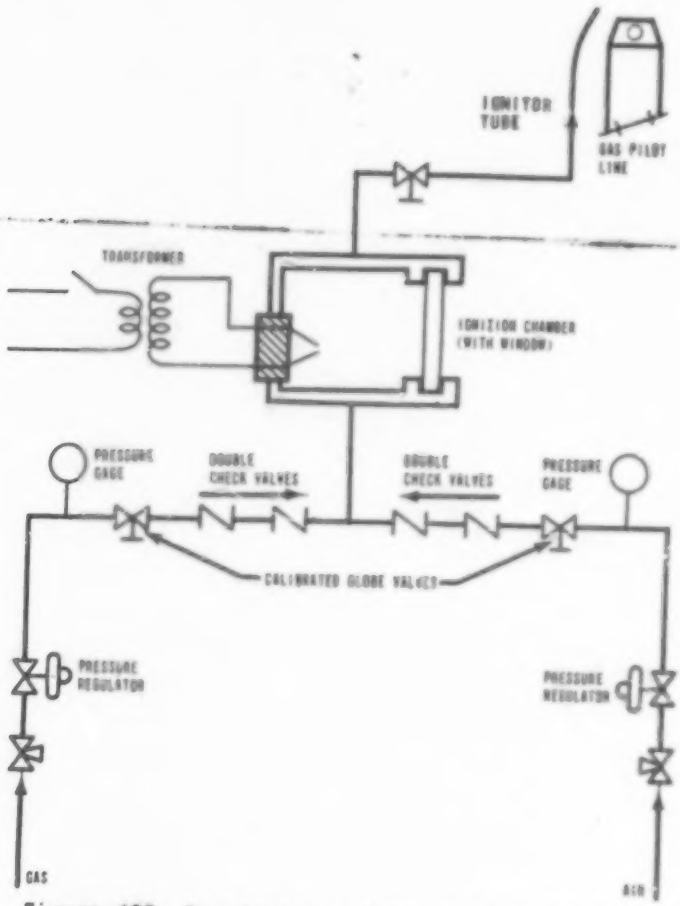


Figure 423. Remote-control system for igniting flare pilot burners (American Petroleum Institute, 1957).

equipped to provide steam automatically and in proportion to the emergency gas flow.

Basically, the instrumentation required for a flare is a flow-sensing element, such as a Pitot tube, and a flow transmitter that sends a signal (usually pneumatic) to a control valve in the steam line. Although the Pitot tube has been used extensively in flare systems, it is limited by the minimum linear velocity required to produce a measurable velocity head. Thus, small gas flows will not actuate the steam control valves. This problem is usually overcome by installing a small bypass valve to permit a constant flow of steam to the flame burner.

A more sensitive type of flow-measuring device is the inverted weir. A typical installation is shown in Figure 424. A variation of the inverted weir is the slotted orifice previously shown in Figure 413. The operation of this installation has already been described.

The hot-wire flow meter has also been used in flare systems (Huebner, 1959). The sensing element is basically a heat loss anemometer consisting of an electrically heated wire exposed to the gas stream to measure the velocity. The gas flow is perpendicular to the axis of the hot wire. A conventional recorder is used with this probe, modified for the resistance bridge circuit of the gas flow meter. As the flow of

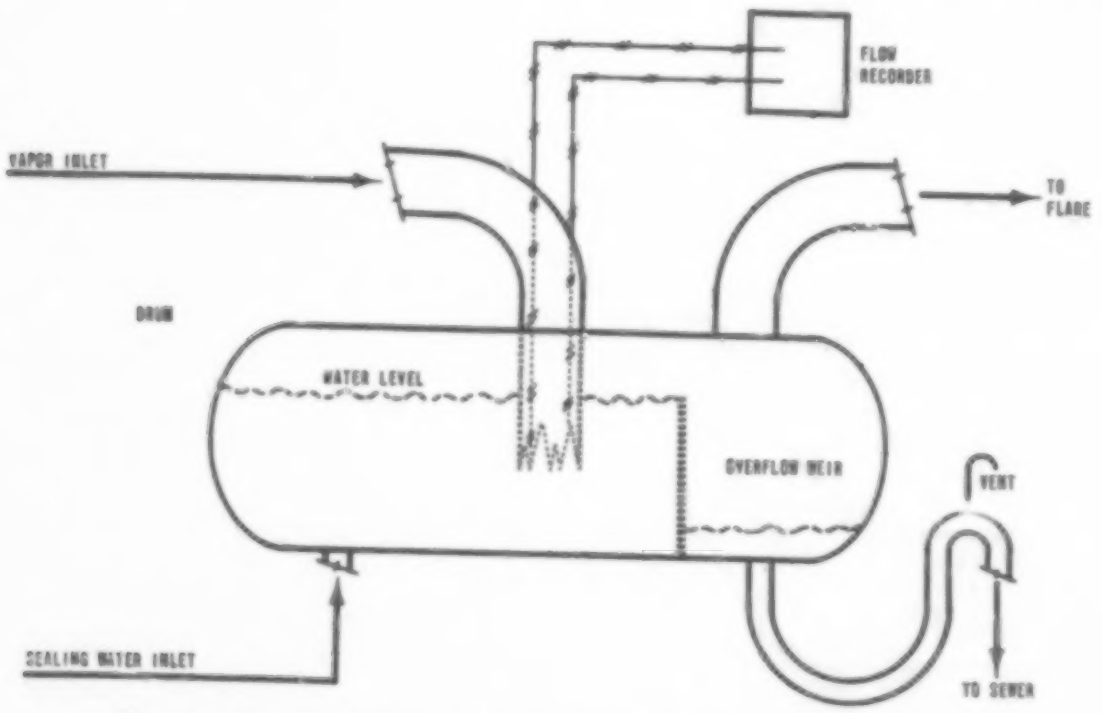


Figure 424. Inverted weir for measuring gas flow to a flare. The end of the low-pressure line to the flow recorder should be at the same level as the tops of the slots in the inverted weir. The end of the high-pressure line to the recorder should be at the same level as the bottoms of the weir slots (American Petroleum Institute, 1957).

gas past the probe varies, the heat loss from the hot wire varies and causes an imbalance of the bridge circuit. The recorder then adjusts for the imbalance in the bridge and indicates the gas flow. This type of installation provides sensitivity at low velocities, and the gas flow measurement can be made without causing an appreciable pressure drop. This is an important advantage in a system using constant backpressure-type relief valves. One flow meter of this type in use has a velocity range of 0 to 6,000 fpm. The hot-wire flow meter can be used as a primary flow-sensing element or as a leak detector in laterals connected to the main flare header.

Another system using a venturi tube as the primary element for measuring the rate of gas flow to a flare is shown in Figure 425.

Supply and control of steam

After the amount of steam required for maximum design gas flow rates is determined, the size of the steam supply line can be estimated by conventional methods of calculation, such as shown in Figure 426. The following example illustrates the calculations for sizing the steam supply line.

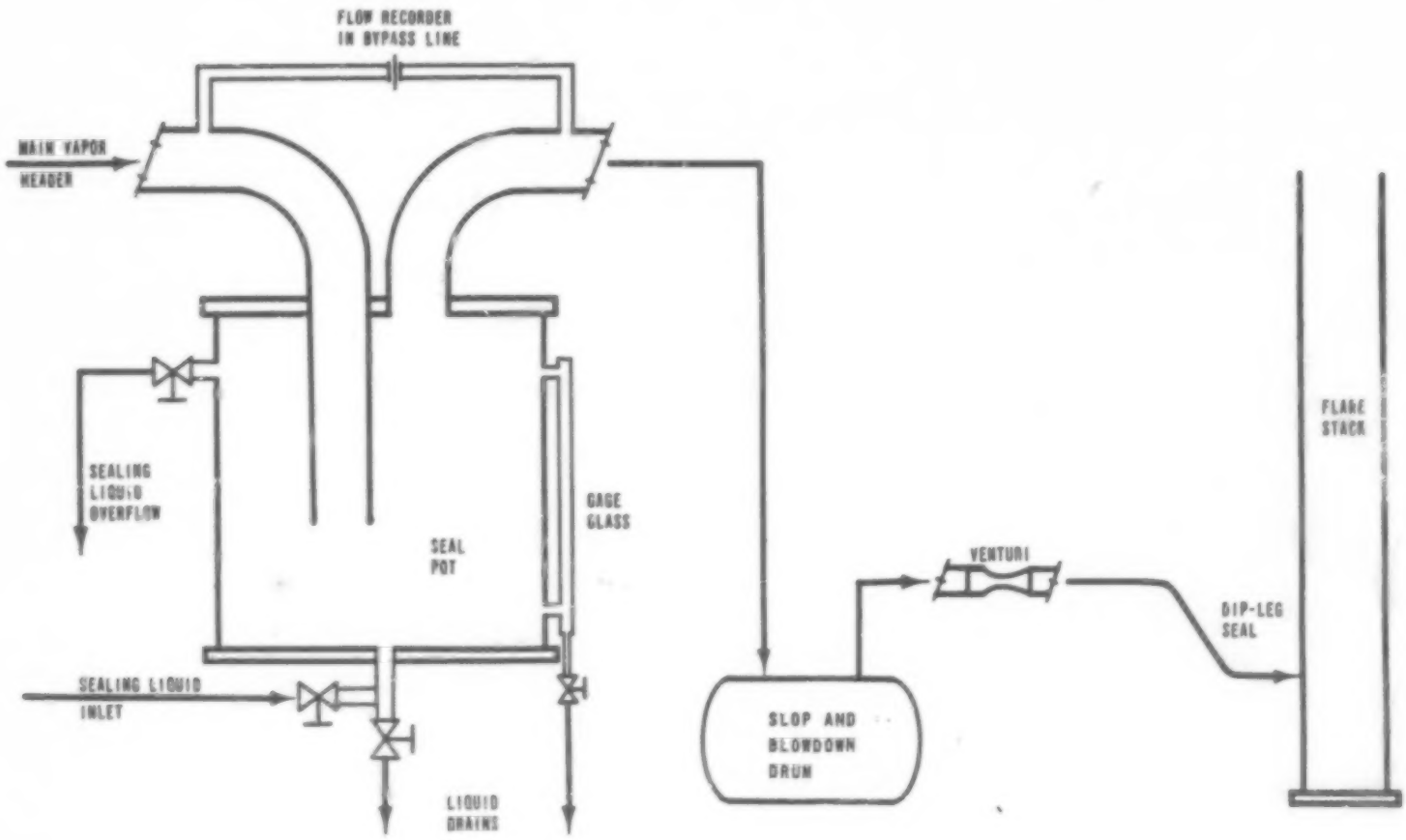


Figure 425. System for measuring flare gas. Small flows of gas are measured by the flow recorder in the bypass line. When a blow occurs that is large enough to overcome the static head of the sealing liquid in the seal pot, the liquid is blown to the slop and blowdown drum. The gas flow is measured by the venturi in the main line to the flare (American Petroleum Institute, 1957).

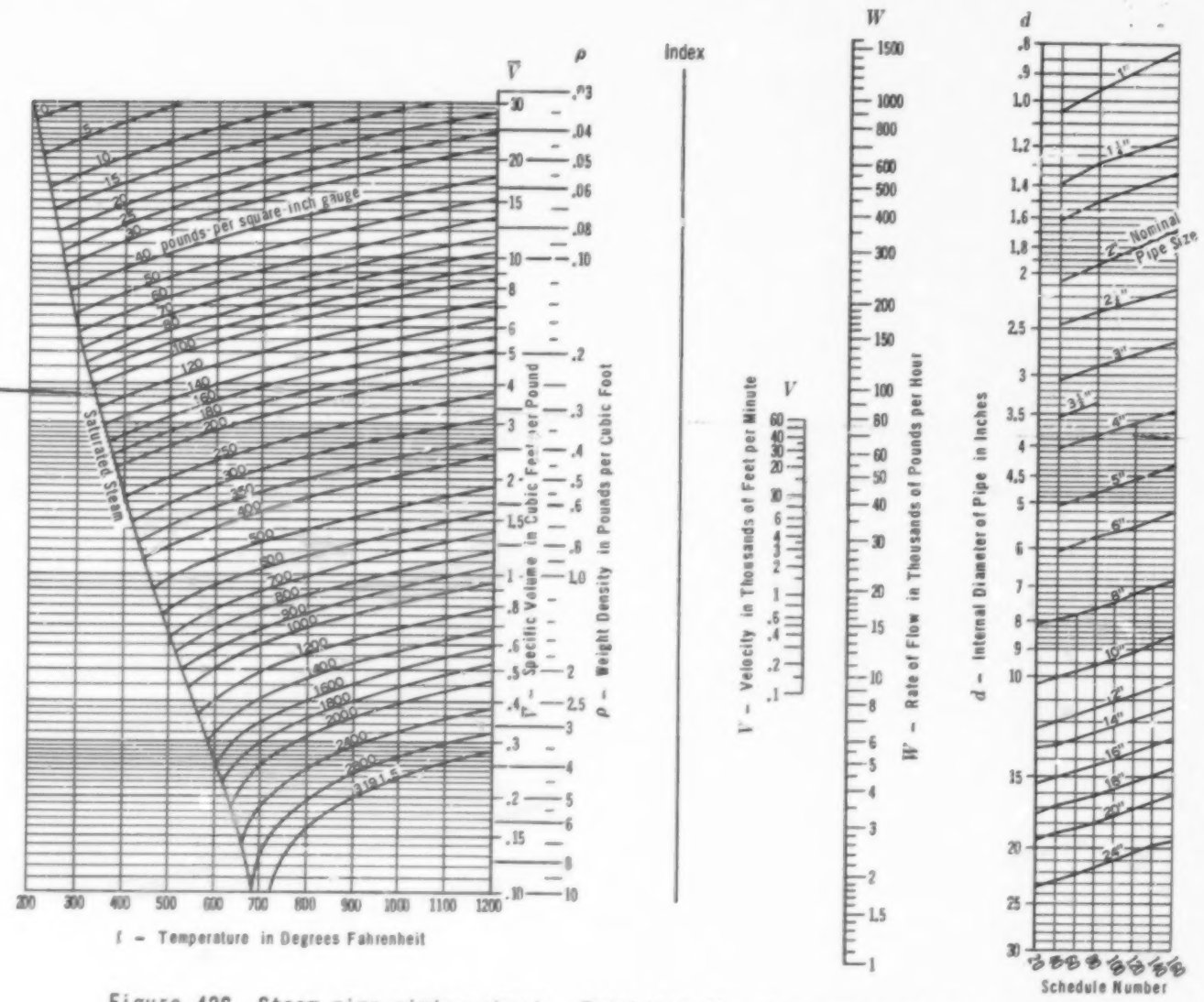

V
ρ
Index
W
d
pounds-per-square-inch gauge
Saturated Steam
Specific Volume in Cubic Feet per Pound
ρ - Weight Density in Pounds per Cubic Foot
t - Temperature in Degrees Fahrenheit
V - Velocity in Thousands of Feet per Minute
W - Rate of Flow in Thousands of Pounds per Hour
d - Internal Diameter of Pipe in Inches
Nominal Pipe Size
Schedule Number

Figure 426. Steam pipe sizing chart. Establish the steam pressure and temperature intersection. Draw a horizontal line to specific volume scale $\bar{V}$. Draw a line from V to the expected rate of flow, W. Mark the intersect with the index line. Using either known quantity, pipe size, d; or velocity, V; find the unknown by drawing a line from the index to the known quantity (Crane Company, 1957).

Example 37

Given:

200 psig (215 psia) saturated steam

9,000 lb/hr propane

1,000 lb/hr propylene

10% (by weight) unsaturated material.

Problem:

Determine the size of the steam supply line required.

Solution:

From Figure 422, the steam-to-hydrocarbon ratio should be 0.55.

Steam required = (10,000 lb/hr)(0.55) = 5,500 lb/hr

With allowance for a future increase in steam requirements, the steam line should be designed to provide 7,000 lb/hr at a velocity of 6,000 fpm. From Figure 426, the pipe diameter is found to be 3 inches.

The number and size of steam jets can be estimated by the following empirical equation (Marks, 1951) for steam flow through a small nozzle:

$$W = 0.0165\, A P_1^{0.97} \qquad (122)$$

where

W = steam flow, lb/sec

A = nozzle area, $in.^2$

P_1 = upstream pressure, psia.

Commercial burners use 1/8- to 1/2-inch-diameter stainless steel pipe for the steam jets with orifices of 1/8 to 7/16 inch in diameter. The number of jets depends upon the gas flow rates and the steam to be delivered into the combustion zone.

Figure 427 is a plot of steam flow versus upstream pressure for various sizes of jet orifices. This chart may be used for preliminary design or for checking an existing installation as shown in Example 38.

Example 38

Given:

Steam flow, 5,500 lb/hr

Available pressure upstream of jets, 80 psia

Assume jet orifice diameter, 3/8 in.

Problem:

Determine minimum number of steam jets required.

Solution:

From Figure 427, the steam flow per jet = 460 lb/hr

$$\text{Number of jets required} = \frac{5,500 \text{ lb/hr}}{460 \text{ lb/hr}} = 11.97$$

Use 12 steam jets with 3/8-inch orifices.

As shown in Figure 428, a jet located at an acute angle to the direction of a gas flow improves the mixing of the gas with air or steam. Commercial flare burners usually have steam jets placed at angles of 15 to 60 degrees with the gas flow.

A steam control system is provided to ensure correct proportions of gas and steam flow. A control valve with equal percentage characteristics is often used in this application. A diagram of this type of valve is shown in Figure 429. Flow curves for valves with various characteristics are shown in Figure 430. The manufacturer's literature should be consulted for specific valves.

Accurate selection of the size of steam control valve requires a full knowledge of the actual flowing conditions. In most cases, the pressure

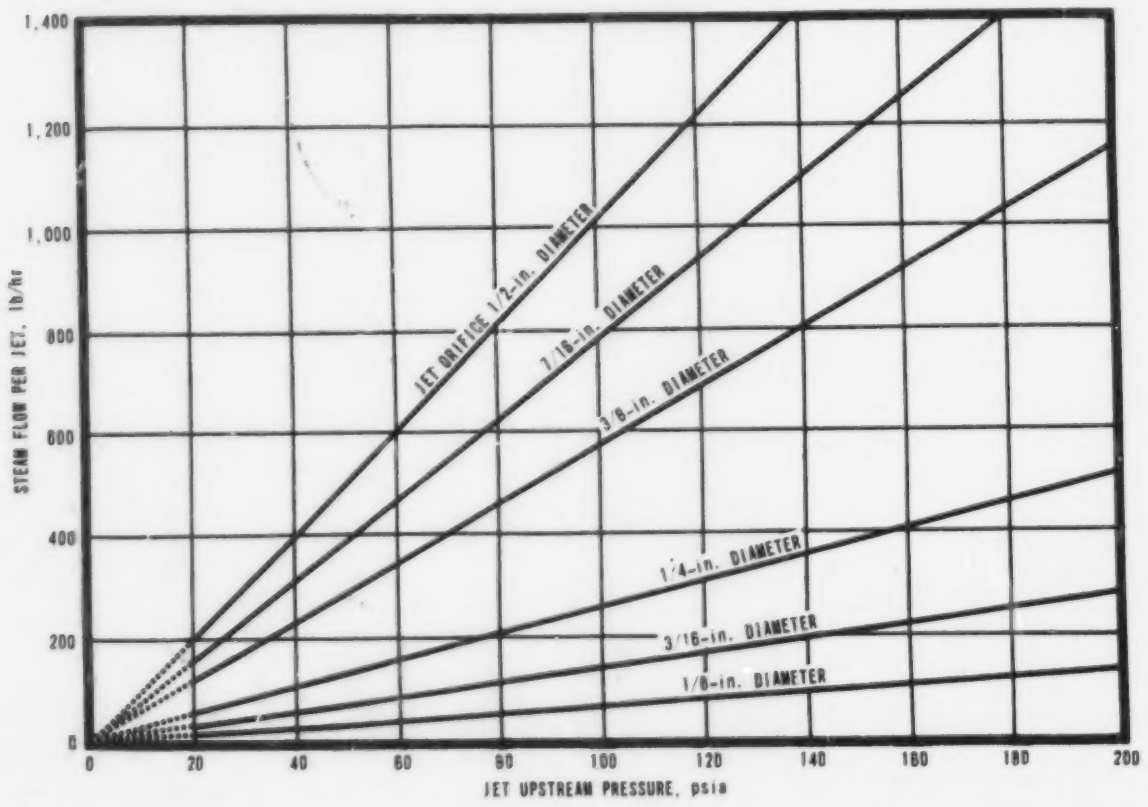


Figure 427. Jet upstream pressure versus jet capacity (based on equation $W = 0.0165\ AP$ where $P < 0.575\ P_{atm}$).

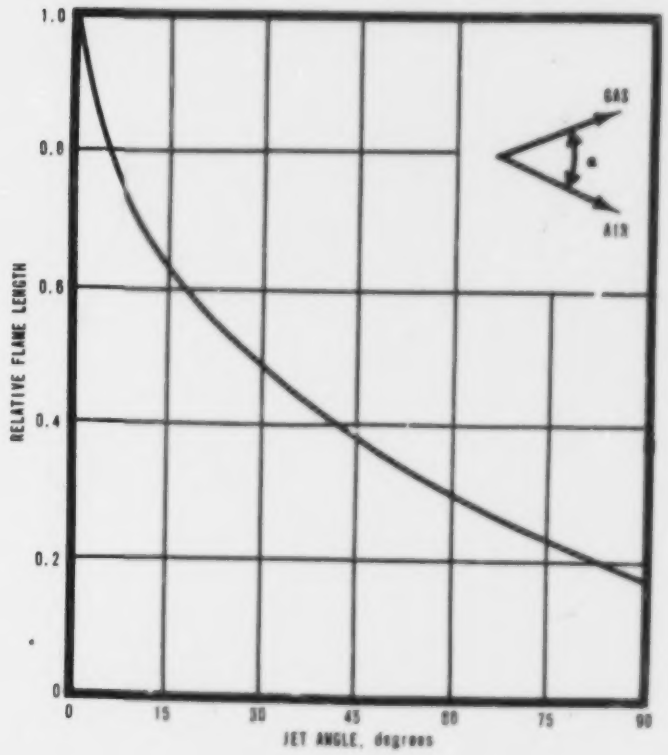


Figure 428. Relationship between flame length and jet angle (Gumz, 1950).

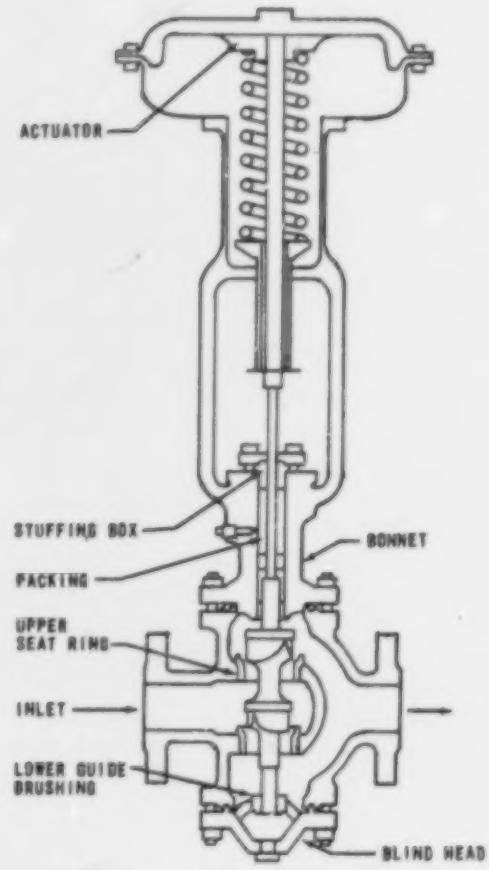


Figure 429. Diagram of double-seated, V-port control valve and valve power unit (Holzbock, 1959).

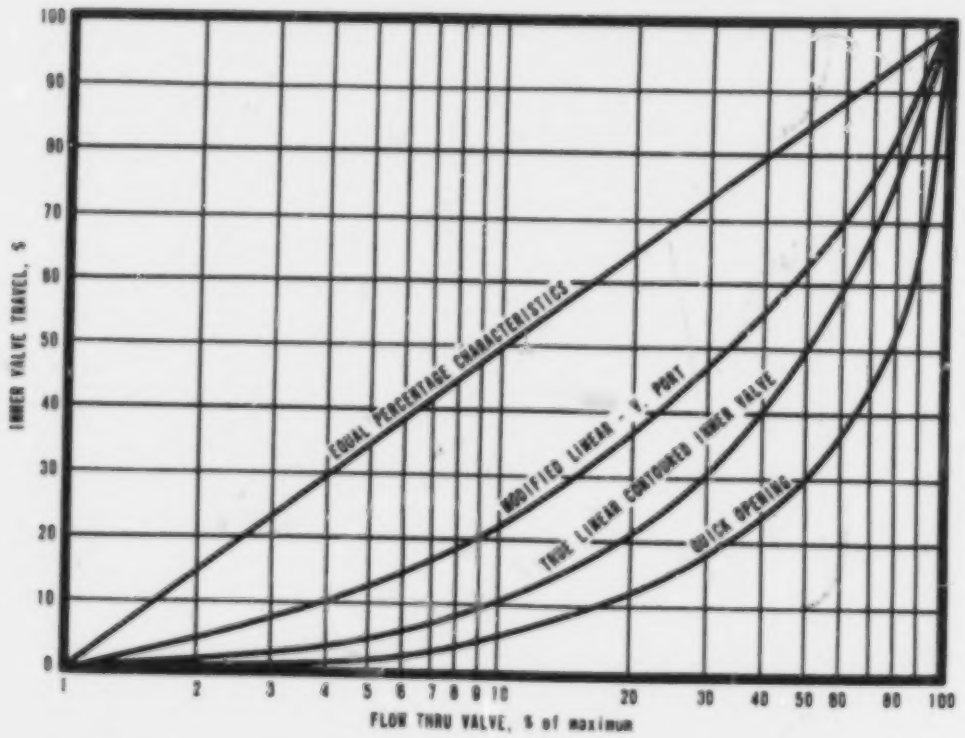


Figure 430. Flow curves for control valves with characterized plugs (Lieblich, 1953).

across the valve must be estimated. A conservative working rule is that one-third of the total system pressure drop, including all fittings and equipment, should be absorbed by the control valve. The pressure drop across valves in long lines or high-pressure drop lines may be somewhat lower. In these cases the pressure drop should be at least 15 to 25 percent of the total system drop, provided the variations in flow rates are small. A control valve can regulate flow only by absorbing energy and giving a pressure drop to the system.

The most convenient method of sizing control valves involves the use of the flow coefficient, C_v. This flow coefficient is essentially a capacity index of the valve and can be obtained from the manufacturer's literature.

By using the basic conversion formulas shown in Table 163, the flow coefficient for any restriction can be determined. Under special conditions, such as a high pressure drop or use of special designs, deviation from the simple fundamental law can be substantial. For most practical valve-sizing problems, the use of the simplified formulas is adequate.

A brief method of selection of a control valve is explained in the following example.

Example 39

Given:

Gas flow, 10,000 lb/hr

Steam-to-hydrocarbon ratio, 0.55 (by wt)

Maximum steam flow, 5,500 lb/hr

P_1, upstream pressure, 160 psig

P_2, downstream pressure, 100 psig

Steam density, downstream, 0.226 lb/ft^3.

Problem:

Select a control valve for this system.

Solution:

Determine C_v from the formula as shown in Table 163:

$$C_v = \frac{W}{2.1\,[(P_1 - P_2)(P_1 + P_2)]^{1/2}} \qquad (123)$$

$$= \frac{5,500}{2.1\,[(174.7 - 114.7)(174.7 + 114.7)]^{1/2}}$$

$$= 19.8$$

A valve with a C_v of 19.8 is indicated. Since an equal percentage characteristic is desired in this application, a correction factor should be applied. This adjustment is necessary because of the flow characteristics of this type of valve. It is suggested by the manufacturer that a 20 percent increase in the C_v be taken to com-

Table 163. EQUATIONS FOR CONTROL VALVE SIZING
(Mason-Neilan Division, 1963)

NOMENCLATURE FOR C_v FORMULAS

V = flow in U.S. gpm
Q = cfh @ 14.7 psia and 60°F
W = lb/hr
P_1 = inlet pressure – psia (14.7 + psi guage)
P_2 = outlet pressure – psia (14.7 + psi gauge)
G = gas sp. gr. (air = 1.0)
G_f = sp. gr. @ flowing temperature
T_f = flowing temperature – °F abs. (460 + °F)
T_{sh} = superheat in °F

Desired	Known	Liquid		Gas		Saturated ① Steam lb/hr	Superheated ① Steam lb/hr
		U.S. gpm	lb/hr	① scfh	① lb/hr		
C_v	V, Q or W G, P_1 & P_2 G_f	$=\frac{V\sqrt{G_f}}{\sqrt{P_1-P_2}}$	$=\frac{W}{500\sqrt{(P_1-P_2)G_f}}$	② $=\frac{Q\sqrt{G}}{42.2\sqrt{(P_1-P_2)(P_1+P_2)}}$	$=\frac{W}{3.22\sqrt{(P_1-P_2)(P_1+P_2)G_f}}$	$=\frac{W}{2.1\sqrt{(P_1-P_2)(P_1+P_2)}}$	$=\frac{(1+0.0007T_{sh})W}{2.1\sqrt{(P_1-P_2)(P_1+P_2)}}$
C_v Temp. Corrected	Q G, P_1 & P_2 T_f			$=\frac{Q\sqrt{GT_f}}{963\sqrt{(P_1-P_2)(P_1+P_2)}}$			
W (lb/hr) V (U.S. gpm) Q (scfh)	C_v G, P_1 & P_2 G_f	$=\frac{C_v\sqrt{P_1-P_2}}{\sqrt{G_f}}$	$=500C_v\sqrt{(P_1-P_2)G_f}$	② $=\frac{42.2C_v\sqrt{(P_1-P_2)(P_1+P_2)}}{\sqrt{G}}$	$=3.22C_v\sqrt{(P_1-P_2)(P_1+P_2)G_f}$	$=2.1C_v\sqrt{(P_1-P_2)(P_1+P_2)}$	$=\frac{2.1C_v\sqrt{(P_1-P_2)(P_1+P_2)}}{(1+0.0007T_{sh})}$
Q (gas) Temp. Corrected	C_v G, P_1 & P_2 T_f			$=\frac{963C_v\sqrt{(P_1-P_2)(P_1+P_2)}}{\sqrt{GT_f}}$			

① When P_2 is less than $\frac{P_1}{2}$ the expression $\sqrt{(P_1-P_2)(P_1+P_2)}$ becomes $0.87P_1$.

② On gas flow the effect of flowing temperatures may be neglected for all temperatures between 30°F and 150°F. For higher or lower temperatures a correction should be included.

pensate for this adjustment. Thus the C_v for the equal percentage valve would be 23.8.

Other items to consider in the selection of control valves are the valve actuator, valve positioners, and future steam requirements. The control valve actuator supplies the power for operating the valve. In flare applications the power unit is usually a pneumatic-spring-diaphragm-type actuator of the type shown in Figure 423, operated by 3 to 15 psig air pressure. These units are designed to open the valve if the air pressure fails. Selection of valve actuators can be made by referring to manufacturer's literature.

Control valve positioners are devices that position the valve stem to match the controller's output signal. The valve plug is thus moved to the desired position, overcoming the packing friction and unbalanced forces in the system. Positioners are also used when split-range valves are operated by one controller. In most elevated-flare installations, the range of gas flow is such that one steam valve does not properly proportion the steam flow, and two parallel steam valves are required. This means that one valve moves from closed to open when the controller output changes from 3 to 9 psig, and the other valve is operated when the controller output is 9 to 15 psig.

Where future steam requirements may be expected to increase, the steam supply line and control valves can be sized for the expected larger capacity. Smaller inner-valve plugs can then be used in the control valves to supply the necessary reduced capacity while the larger body size is retained. The smaller plugs have the same flow characteristics as the standard size plugs, but flow can be reduced as low as 40 percent of nominal capacity.

Design of water-injection-type ground flares

Designing a typical water injection flare consists of sizing the stack structure and combustion airports, and determining the water required to obtain smokeless combustion (American Petroleum Institute, 1957).

With the three-concentric-stack-type flare as previously discussed, the air ports in the intermediate and outer stacks should be designed to admit 150 percent of the theoretical air for complete combustion. The draft for these stacks can be calculated from the equation

$$h = H \frac{\rho_a \rho_v}{\rho_w} \qquad (124)$$

where

h = draft, in. of water

H = height of stack, ft

ρ_a = density of cold air, lb/ft^3

ρ_v = density of hot gas in stack, lb/ft^3

ρ_w = density of water, lb/ft^3.

The area of the stack's arches can be calculated according to the formula

$$A = \frac{W}{457\ CY\ (h_w)(\rho_a)} \qquad (125)$$

where

A = area of orifice, ft^2

W = rate of flow, lb/hr

C = orifice discharge coefficient, dimensionless

Y = expansion factor, dimensionless

h_w = differential pressure across orifice, in. of water at 60°F

ρ_a = density of air at upstream tap conditions, lb/ft^3.

In this case ρ_a is the density of air at 60°F, Y is assumed to be 1.0, and C is assigned the value of 0.6. Equation 125 can now be reduced to

$$A = \frac{W}{20.9\ h_w} \qquad (126)$$

Test data indicate that water pressure is more important in achieving smokeless burning than the amount of water delivered to the flare. In general, a high water pressure results in better mixing of gas. Higher water pressure is required as the molecular weight and unsaturated content of the gas increase. Table 164 lists water spray pressures required for smokeless burning.

Satisfactory proportioning of the flow of water to the flow of gas is difficult to achieve because the pressure drop required for proper spray nozzle operation is high. Where the opacity of smoke emission is limited, some type of remote manual or automatic control is necessary.

Table 164. WATER SPRAY PRESSURES REQUIRED FOR SMOKELESS BURNING[a]
(American Petroleum Institute, 1957)

Gas rate, mcfh	Unsaturates, % by vol	Molecular weight	Water pressure, psig	Water rate, gpm
200,000	0 to 20	28	30 to 40	31 to 35
150,000	30	33	80	45
125,000	40	37	120	51

[a]The data in this table were obtained with a 1-1/2-inch-diameter spray nozzle in a ground flare with the following dimensions:

	Height, ft	Diameter, ft
Outer stack	30	14
Intermediate stack	12	6
Inner stack	4	2.5

Design of venturi-type ground flares

The venturi-type ground flare, as previously discussed, consists of burners, pilots, ignitors, and control valves.

The total pressure drop permitted in a given installation depends upon the characteristics of the particular blowdown system. In general, the allowable pressure drop through the relief valve headers, liquid traps, burners, and so forth, must not exceed one-half the internal unit's relieving pressure. The burner cut-in schedule is based upon a knowledge of the source, frequency, and quantity of the release gases. Pressure downstream of the control valves must be adequate to provide stable burner operation.

Flare installations designed for relatively small gas flows can use clusters of commercially available venturi burners. For large gas releases, special venturi burners must be constructed. The venturi (air-inspirating) burners are installed in clusters with a small venturi-type pilot burner in the center. This burner should be connected to an independent gas source. The burners may be mounted vertically or horizontally. The burners should fire through a refractory wall to provide protection for personnel and equipment. Controls can be installed to give remote indication of the pilot burner's operation.

For large-capacity venturi burners, field tests are necessary to obtain the proper throat-to-orifice ratio and the minimum pressure for stable burner operation. The design of one flare system using special venturi burners has been reported (Brumbaugh, 1947). An analysis of the burner limitations and the pressure relief system in this installation yielded the design data set forth in Table 165.

Table 165. DESIGN DATA FOR A FLARE SYSTEM USING SPECIAL VENTURI BURNERS
(Brumbaugh, 1947)

Burner No.	Cut-in pressure, psi	Cut-out pressure, psi	Gas orifice diameter, in.	Venturi throat dia, in.	Rates of throat-to-orifice area
1	2-1/4	1/4	1.61	5	9.6
2	2-3/4	1/2	2.90	8	7.8
3	3-1/4	3/4	4.03	11.5	8.1
4	3-3/4	1	7	18	6.6

After 5 years, this flare was reported to be satisfactory and had required relatively few changes (Green, 1952).

The selection of the control valves and burners for a small-capacity ground flare is indicated by the following example:

Example 40

Given:

Range of gas flow, 2,000 to 30,000 cfh

Most frequently expected gas flow, 12,000 cfh

Blowdown line size, 4-in. dia

Specific gravity of gas, 1.2

Calorific value of gas, 1,300 Btu/ft^3

Flowing temperature of gas, 100°F.

Problem:

Select control valves and determine the number and size of standard air-inspirating burners to permit smokeless burning of all expected gas flows.

Solution:

On the basis of the range of expected gas flow, try three banks of burners with a water seal bypass to the largest bank to handle gas flows in excess of flare capacity. The maximum allowable pressure at the burners has been set at 5 psig. Various intermediate pressures for the control valves will be arbitrarily selected. The intermediate pressures, which indicate stable operations of the different burner banks relative to the gas flows, will be used as the operating points for the valves.

1. Valve selection and capacity data:

   Try two 1-inch and one 2-inch single-seated, quick-opening valves.

Valve size, in.	Capacity index, C_v	Pressure, psi	Capacity, cfh
1	14	0.5	2,070
		1.0	2,940
		3.0	5,080
		5.0	6,580
2	46	3.0	15,000
		5.0	20,000

2. Burner selection--No. 1 bank:

No. 1 bank of burners to handle a minimum flow of 2,000 cfh at 0.5 psig.

Try a No. 16X NGE burner with a 1/2-in. orifice.

From Table 166, capacity of a No. 16X burner at 0.5 psig (1,000 Btu/ft^3 gas) is 1,360 cfh.

Table 166. VENTURI BURNER CAPACITIES, ft^3/hr (Natural Gas Equipment, Inc., 1955)[a]

Gas pressure, in. H_2O	Type 14 3/16-in. orifice	Type 16 7/16-in. orifice	Type 16X 1/2-in. orifice
2	70		
4	100		
6	123		
8	142		
10	160		
1/2 psig	210	1,042	1,360
1 psig	273	1,488	1,900
2 psig	385	2,157	2,640
3 psig		2,654	3,200
4 psig		3,065	3,680
5 psig		3,407	4,080
6 psig		3,742	4,480
7 psig		4,040	4,800
8 psig		4,320	5,160

[a]Basis: 1,000 Btu/ft^3 natural gas.

Capacity of 1,300 Btu/ft^3 gas:

$$\frac{1,000}{1,300} \times 1,360 \text{ cfh} = 1,047 \text{ cfh/burner}$$

Number of burners required:

$$\frac{2,000 \text{ cfh}}{1,047 \text{ cfh/burner}} = 1.91 \text{ burners}$$

Use two burners.

No. 1 bank capacity at other operating pressures:

No. of burners	Capacity, cfh			
	0.5 psig	1.0 psig	3.0 psig	5 psig
2	2,094	2,930	4,920	6,270

Range of No. 1 bank burners is 2,000 to 6,000 cfh, with valve capacity range from 2,000 to 7,000 cfh.

3. Burner selection--No. 2 bank:

No. 2 bank of burners to be sized such that capacity of the 1 and 2 banks will equal the most frequently expected flow of 12,000 cfh. Use 6,000 cfh as approximate capacity of No. 1 bank.

12,000 cfh - 6,000 cfh = 6,000 cfh

Size and capacity of No. 2 bank burners and valves will be the same as those of No. 1 bank.

4. Burner selection--No. 3 bank:

No. 3 bank capacity must equal the difference between 30,000 cfh and 12,000 cfh.

30,000 cfh - 12,000 cfh = 18,000 cfh

From Table 166, capacity of No. 16X burner at 5 psig is 4,080 cfh (1,000 Btu/ft^3 gas).

Capacity for 1,300 Btu/ft^3 gas:

$$\frac{1,000}{1,300} \times 4,080 = 3,140 \text{ cfh/burner}$$

Number of burners required:

$$\frac{18,000/\text{cfh}}{3,140 \text{ cfh/burner}} = 5.7 \text{ burners}$$

Use six No. 16X NGE burners.

No. 3 bank capacity at other pressures:

No. of burners	Capacity, cfh	
	3.0 psig	5.0 psig
6	14,760	18,830

Range of No. 3 bank burners, 14,760 to 18,300 cfh, with 2-inch valve range of 15,500 to 20,000 cfh.

5. Safety seal:

Basis: Seal pressure 6 psig
Sealing liquid Water
Temperature 70°F

ft of water =

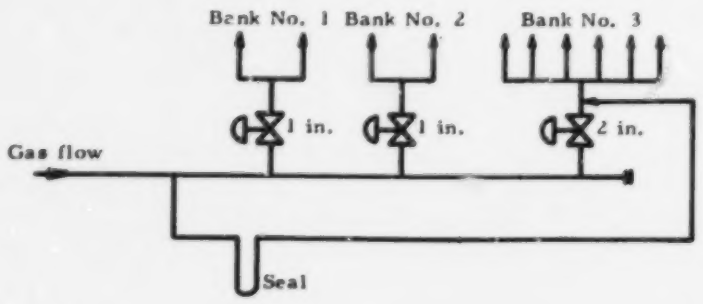
$$\frac{(6 + 14.7)\ \text{lb/in.}^2\ (144)\ \text{in.}^2/\text{ft}^2}{62.3\ \text{lb/ft}^3} = 47.8\ \text{ft}$$

6. Summary of flare operation:

Valve No.	Valve action: Open, psig	Valve action: Closed, psig	Range, psi	Burner capacity at 5 psig	Valve capacity at 5 psig
1	1.0	0.5	0.5-5	6,270	6,580
2	3.0	1.0	1-5	6,270	6,580
3	5.0	3.0	5-6	18,830	20,000
				31,370	33,160

The bypass seal is set to open to No. 3 burner bank at 6 psig.

7. Sketch of flare:



Maintenance of flares

Most refineries and petrochemical plants have a fixed schedule for inspection and maintenance of processing units and their auxiliaries. The flare system should not be exempted from this practice. Removal of a flare from service for maintenance requires some type of standby equipment to disperse emergency gas vents during the shutdown. A simple stack with pilot burner should suffice for a standby. Coordinating this inspection to take place at time when the major processing units are also shut down is good practice.

Flare instrumentation requires scheduled maintenance to ensure proper operation. Most of the costs and problems of flare maintenance arise from the instrumentation.

Maintenance expenses for flare burners can be reduced by constructing them of chrome-nickel alloy. Because of the inaccessibility of elevated flares, the use of alloy construction is recommended.

STORAGE VESSELS

TYPES OF STORAGE VESSELS

Even in the most modern petroleum refineries and petrochemical plants, storage facilities must be provided for large volumes of liquids and gases. These facilities can be classified as closed-storage or open-storage vessels. Closed-storage vessels include fixed-roof tanks, pressure tanks, floating-roof tanks and conservation tanks. Open-storage vessels include open tanks, reservoirs, pits, and ponds.

Closed-storage vessels are constructed in a variety of shapes, but most commonly as cylinders, spheres, or spheroids. Steel plate is the usual material of construction though concrete, wood, and other materials are sometimes used. Before modern welding methods, the sections of the tank shell were joined by rivets or bolts. Welded joints are now used almost universally except for the small bolted tank found in production fields. The definition of a welded shell tank is given by API Standard 12 C entitled "Welded Oil Storage Tanks." Capacities of storage vessels range from a few gallons up to 500,000 barrels, but tanks with capacities in excess of 150,000 barrels are relatively rare.

Open-storage vessels are also found in a variety of shapes and materials of construction. Open tanks generally have cylindrical or rectangular shells of steel, wood, or concrete. Reservoirs, pits, ponds, and sumps are usually oval, circular, or rectangular depressions in the ground. The sides and bottom may be the earth itself or may be covered with an asphalt-like material or concrete. Any roofs or covers are usually of wood with asphalt or tar protection. Capacities of the larger reservoirs may be as much as 3 million barrels.

Vapors, gases, aerosols, and odors are examples of air contaminants emitted from storage facilities. In most cases, practical and feasible air pollution control measures are available to reduce the emissions.

Pressure Tanks and Fixed-Roof Tanks

Pressure tanks and fixed-roof tanks are grouped together because, in a sense, pressure tanks are special examples of fixed-roof tanks designed to operate at greater than atmospheric pressure. A horizontal, cylindrical (bullet) pressure tank is shown in Figure 431. Other

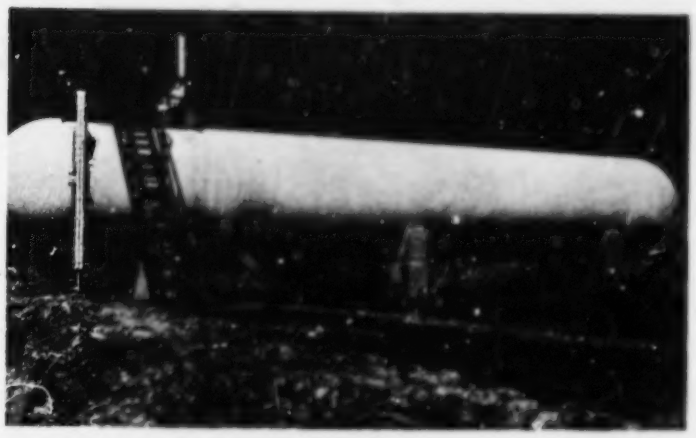


Figure 431. Horizontal, cylindrical pressure tank (Graver Tank and Manufacturing Company, Division Union Tank Car Co., East Chicago, Indiana).

types of pressure tanks--spheres, plain and noded spheroids, and noded hemispheroids--are illustrated in Figure 432. Maximum capacities of these pressure tanks are as much as 30,000 barrels for spheres and hemispheroids, and 120,000 barrels for noded spheroids. Spheres can be operated at pressures up to 217 psi; spheroids, up to 50 psi; noded spheroids, up to 20 psi; and plain or noded hemispheroids, up to 15 and 2-1/2 psi respectively. Horizontal, cylindrical pressure tanks are constructed with various capacities and pressures.

The ordinary vertical, cylindrical, fixed-roof tank is shown in Figure 433. This type of storage facility operates at or within a few ounces of pressure and may have a flat, recessed flat, conical, or domed roof. The term gastight, often applied to welded tanks, is misleading. Many of the roofs of the welded tanks have free vents open to the atmosphere. Others are equipped with conservation vents that open at very slight positive pressures. A tank also has many standard appurtenances including gaging hatches, sample hatches, relief vents, and foam mixers. Any of these accessories may fail in service and result in vapor leaks.

The operating pressure of a tank is limited by the thickness (weight) of the roof, as noted in Table 167. A cone roof tank may be operated at higher pressures, if necessary, by structural reinforcement or weighting of the roof. Safe operating pressures up to 4 ounces can be realized by this added expense. Use of unsupported dome-shaped roofs is another method of increasing the allowable operating pressure of the fixed-roof tank.

Floating-Roof Tanks

Floating-roof storage tanks are used for storing volatile material with vapor pressures in the low-

Table 167. ROOF PROPERTIES OF STEEL TANKS (Bussard, 1956)

Thickness, in. (gage)	Wt, lb/ft^2	Operating pressure, oz/in.^{2}
1/16 (16)	2.553	0.284
5/64 (14)	3.187	0.354
7/64 (12)	4.473	0.497
1/8 (11)	5.107	0.568
9/64 (10)	5.740	0.638
5/32 (9)	6.374	0.708
11/64 (8)	7.000	0.778
3/16 (7)[a]	7.650	0.850
1/4 (3)	10.200	1.333

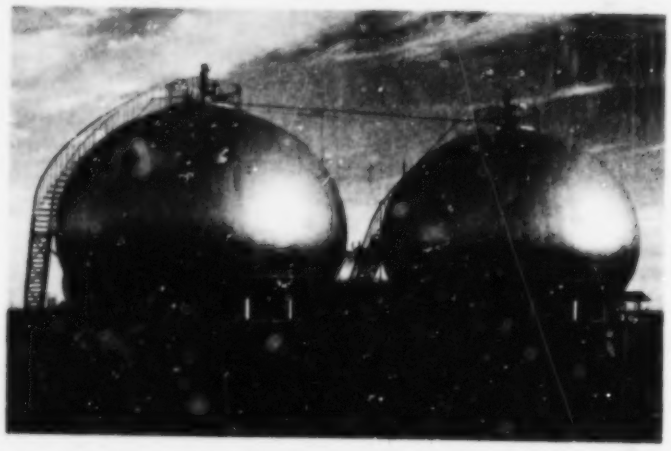
[a]Minimum thickness specified by API Std 12C.

er explosive range, to minimize potential fire or explosion hazards. These vessels also economically store volatile products that do not boil at atmospheric pressures or less and at storage temperatures or below. These tanks are subclassified by the type of floating-roof section as pan, pontoon, or double-deck floating-roof tanks (Figure 434).

Pan-type floating-roof tanks were placed in service more than 40 years ago. These roofs require considerable support or trussing to prevent the flat metal plate used as the roof from buckling (Figure 434, lower right). These roofs are seldom used on new tanks because extreme tilting and holes in the roof have caused more than one-fifth of installed pan roofs to sink, and because their use results in high vaporization losses. Solar heat falling on the metal roof in contact with the liquid surface results in higher than normal liquid surface temperatures. Hydrocarbons boil away more rapidly at the higher temperatures and escape from the opening around the periphery of the roof.

To overcome these disadvantages, pontoon sections were added to the top of the exposed deck. Better stability of the roof was obtained, and a center drain with hinged or flexible connections solved the drainage problem. Center-weighted pontoons, double pontoons, and high- and low-deck-pontoon floating-roof tanks are available today. Current practice is to use the pontoon roof on tanks with very large diameters. Included with some pontoon roof designs is a vapor trap or dam installed on the underside of the roof. This trap helps retain any vapors formed as a result of localized boiling and converts the dead vapor space into an insulation medium. This dead vapor space tends to retard additional boiling.

The more expensive double-deck floating roof was eventually introduced to reduce the effect of solar boiling and to gain roof rigidity. The final design



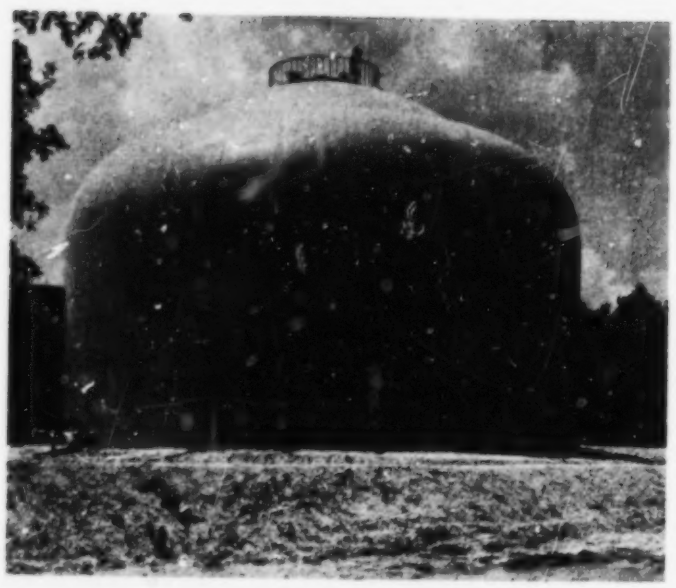


Figure 432. Types of pressure vessels: (upper left) 51-foot-diameter spheres (Butane is stored in these spheres at a petroleum refinery in California. Capacity of each is 15,000 barrels, diameter is 54 feet 9 inches and design working pressure is 35 pounds per square inch.); (upper right) two 5,000-barrel spheroids designed for 20-psi pressure; (lower left) large noded spheroids, each designed for 100,000-barrel capacity and 15-psi pressure; (lower right) a 20,000-barrel noded hemispheroid designed for 2-1/2-psi pressure (Chicago Bridge and Iron Company (1959).

generally incorporates compartmented dead-air spaces more than 12 inches deep over the entire liquid surface. The top deck is generally sloped toward the center or to a drainage area. Any liquid forming or falling on the roof top is drained away through a flexible roof drain to prevent the roof from sinking. The bottom deck is normally coned upwards. This traps under the roof any vapors entrained with incoming liquid or any vapors that might form in storage. A vertical dam similar to those used on pan or pontoon floating roofs can also be added to retain these vapors.

Conservation Tanks

Storage vessels classified as conservation tanks include lifter-roof tanks and tanks with internal, flexible diaphragms or internal, plastic, floating blankets. The lifter roof or, as more commonly known, gas holder, is used for low-pressure gaseous products or for low-volatility liquids. This type of vessel can be employed as a vapor surge tank when manifolded to vapor spaces of fixed-roof tanks.

Figure 433. Vertical, cylindrical, fixed-roof storage tank.

Two types of lifter-roof tanks are available, as shown in Figure 435. One type has a dry seal consisting of a gastight, flexible fabric; the other type employs a liquid seal. The sealing liquid can be fuel oil, kerosene, or water. Water should not be employed as a sealing liquid where there is danger of freezing.

The physical weight of the roof itself floating on vapor maintains a slight positive pressure in the lifter-roof tank. When the roof has reached its maximum height, the vapor is vented to prevent overpressure and damage to tank.

The conservation tank classification also includes fixed-roof tanks with an internal coated-fabric diaphragm, as shown in Figure 436. The diaphragm is flexible and rises and falls to balance

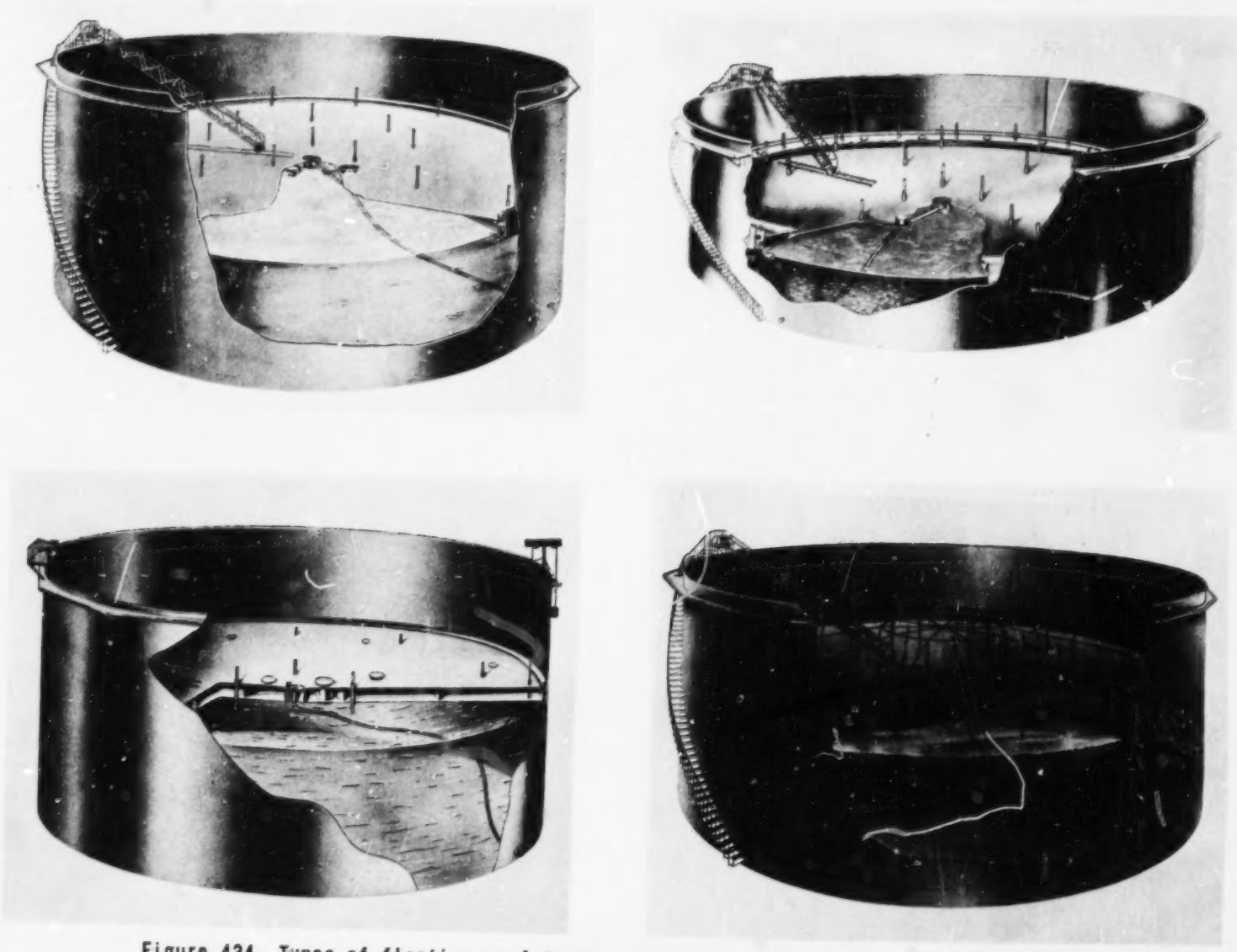


Figure 434. Types of floating-roof tanks: (upper left) Sectional view of single-deck center-weighted (pan-type) floating roof; (upper right) sectional view of pontoon deck floating roof; (lower left) cutaway view of double-deck floating roof; (lower right) cutaway view of trussed-pan floating roof (Graver Tank and Manufacturing Company, East Chicago, Ind.).

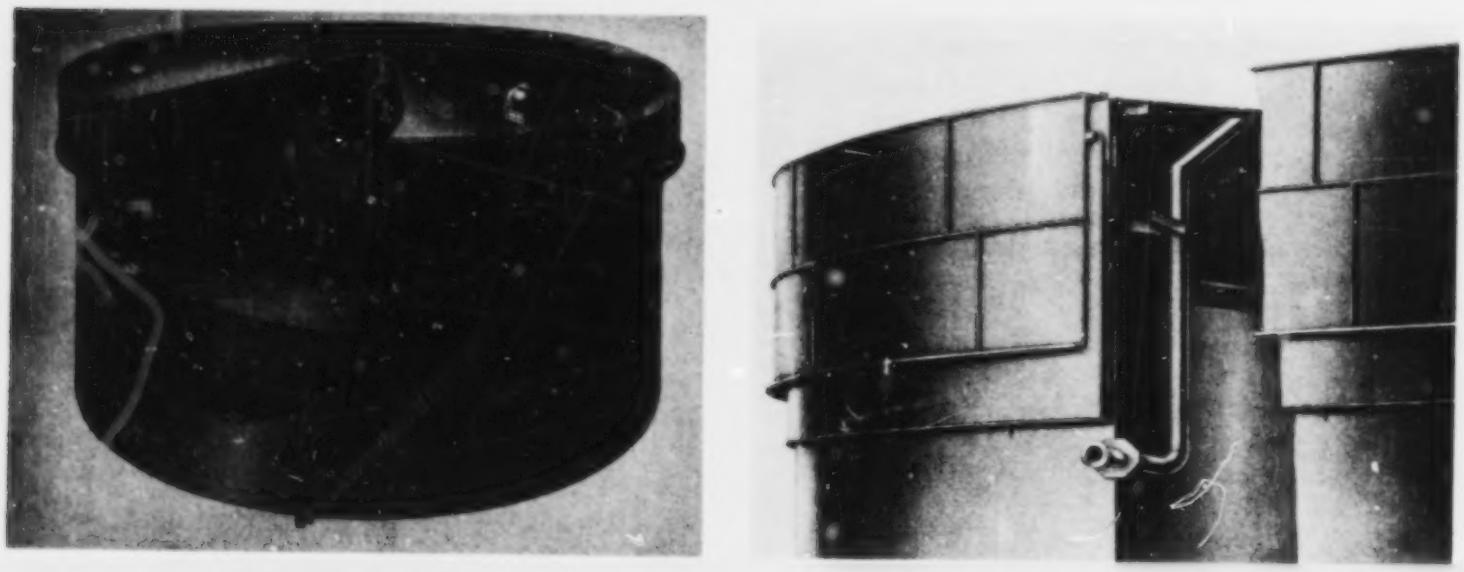


Figure 435. Types of lifter-roof tanks: (left) Sectional view of expansion roof tank with a liquid seal, (right) closeup view of liquid seal and vapor piping (Graver Tank and Manufacturing Co., Division of Union Tank Car Co., East Chicago, Indiana).

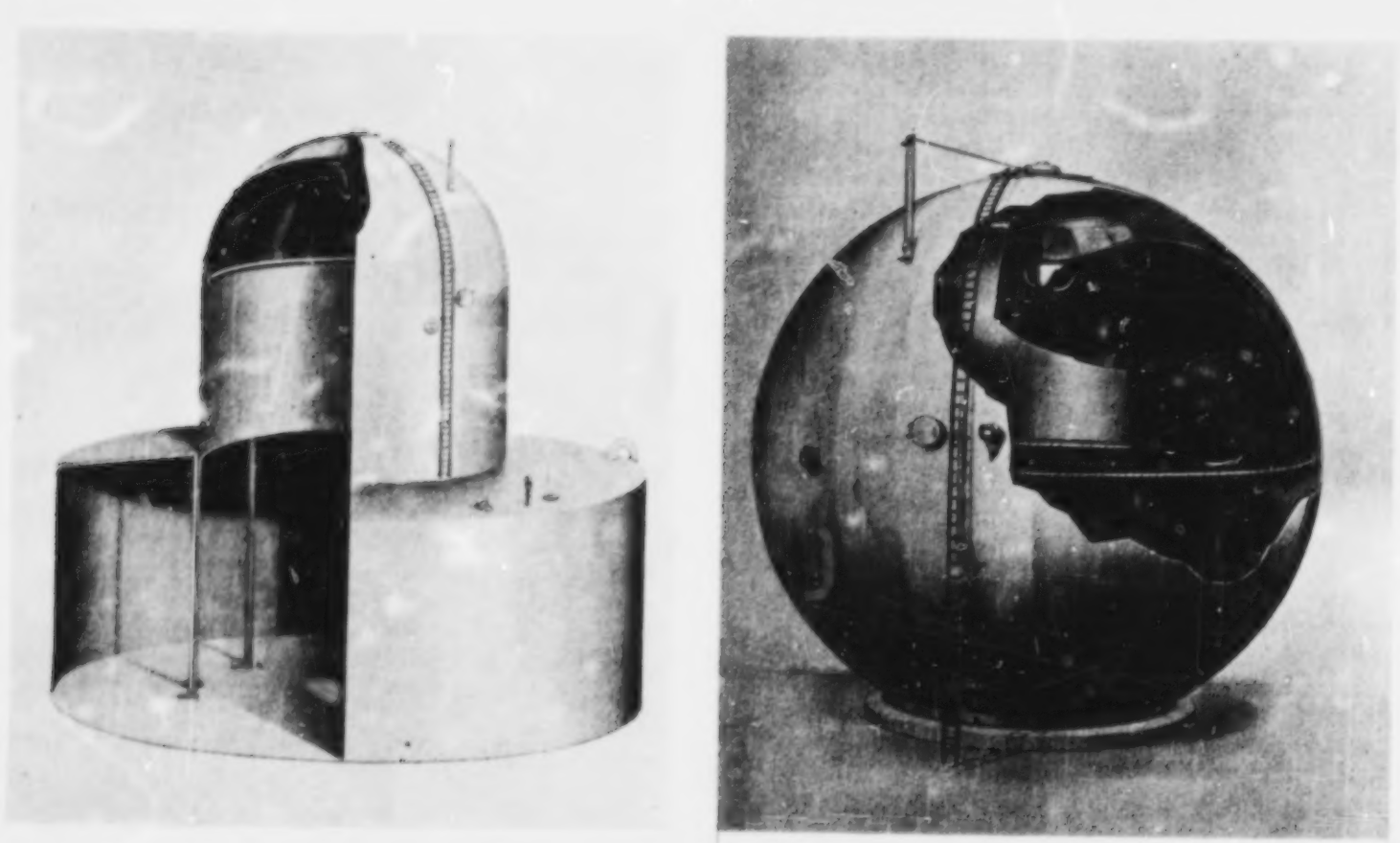


Figure 436. Conservation tanks; (left) Sectional view of integrated conservation tank with internal, flexible diaphragm; (right) cutaway view of a vapor conservation tank showing flexible membrane (Chicago Bridge and Iron Co., Chicago, Ill.).

pressure is 1/2 ounce per square inch, which is approximately one-eighth the operating pressure possible with most gas holders. Two basic types of diaphragm tanks are the integrated tank, which stores both liquid and vapor, and the separate tank, which stores only vapor. Common trade names for integrated tanks are "diaflote," "dialift," and "vapor-mizer" tanks (Bussard, 1956), or they may be referred to as vapor spheres or vapor tanks. The separate type of tank offers more flexibility and does not require extensive alteration of existing tanks.

Open-Top Tanks, Reservoirs, Pits, and Ponds

The open-top tank is not used as extensively as in the past. Safety, conservation, and housekeeping are factors effecting the elimination of open vessels. Even tanks that require full access can and should be equipped with removable covers. The open vessels generally have a cylindrical shell, but some have a rectangular shell.

Reservoirs were devised to store the large quantities of residual oils, fuel oils, and, sometimes, crude oils resulting from petroleum production and refining. Safety considerations, larger fixed-roof tanks, and controlled crude oil production have reduced the number of reservoirs in use today. Even when covered, reservoirs have open vents, which maintain atmospheric pressures in the reservoir. Windbreaks divert the windflow pattern over a large roof area and prevent the roof from raising and buckling.

Open ponds or earthen pits were created by diking low areas or by excavation. These storage facilities served for holding waste products, refinery effluent water, or inexpensive oil products for considerable periods of time. In these, oils "weathered" extensively, leaving viscous, tar-like materials, and water seeped into the lower ground levels. As the pond filled with solids and semisolids, the contents were removed by mechanical means, covered in place, or the pond was simply abandoned. The use of these ponds has diminished, and the remaining ponds are usually reserved for emergency service.

Smaller ponds or sumps were once used extensively in the crude oil production fields. This use was primarily for drilling muds though oil-water emulsions and crude oil were also stored by this method. Their use is gradually disappearing because unattended or abandoned sumps cause nuisance problems to a community.

THE AIR POLLUTION PROBLEM

Different types and quantities of air pollution can be associated with the storage vessel. The types of pollution can be separated into three categories--vapors, aerosols or mists, and odors. Of these pollutants, the largest in quantity and concentration are hydrocarbon vapors.

Factors Affecting Hydrocarbon Vapor Emissions

Emissions of hydrocarbon vapors result from the volatility of the materials being stored. They are effected by physical actions on the material stored or on the storage itself. Changes in heat or pressure change the rate of evaporation. Heat is a prime factor and can cause unlimited vaporization of a volatile liquid. Heat is received from direct solar radiation or contact with the warm ambient air, or is introduced during processing. The rate of evaporation is correlated with atmospheric temperature, weather conditions, tank shell temperature, vapor space temperature, and liquid body and surface temperatures.

The vapor space of a tank can contain any degree of saturation of air with vapor of the liquid up to the degree corresponding to the total vapor pressure exerted by the liquid at storage temperatures. Since the pressure in this vapor space increases with temperature increase, some of the air-vapor mixture may have to be discharged or "breathed out" to prevent the safe operating pressure of the tank from being exceeded. These emissions are continually promoted by the diurnal change in atmospheric temperatures, referred to as the tank's breathing cycle.

When the air temperature cools, as at night, the vapor space within the tank cools and the vapors contract. Fresh air is drawn in through tank vacuum vents to compensate for the decrease in vapor volume. As this fresh air upsets any existing equilibrium of saturation by diluting the vapor concentration, more volatile hydrocarbons evaporate from the liquid to restore the equilibrium. When the atmospheric temperature increases, as occurs with daylight, the vapor space warms, and the volume of rich vapors and the pressure in the tank increase. In freely vented tanks, or when the pressure settings of the relief vents have been exceeded, the vapors are forced out of the tank. This cycle is repeated each day and night. Variation in vapor space temperature also results from cloudiness, wind, or rain.

Filling operations also result in expulsion of part or all of the vapors from the tank. The rate and quantity of vapor emissions from filling are directly proportional to the amount and the rate at which liquid is charged to the vessel. Moreover, as the liquid contents are withdrawn from the tank, air replaces the empty space. This fresh air allows more evaporation to take place.

Another emission of vapors caused by atmospheric conditions is termed a windage emission. This emission results from wind's blowing through a free-vented tank and entraining or educting some of the saturated vapors. The windage emission is not as large as that occurring during breathing or filling cycles. Other variables affecting emissions include: Volume of vapor space, frequency of filling, and vapor tightness of the vessel. Tanks that can be kept completely full of liquid limit the volume of the vapor space into which volatile hydrocarbons can vaporize and eventually be emitted to the atmosphere. The frequency of filling and emptying a tank influences the overall vapor emissions. When extensive periods of time elapse between pumping operations, the vapor space of a tank becomes more nearly fully saturated with vapor from the liquid. Then, during filling of the tank or during breathing cycles, a larger concentration of vapors exists in the air-vapor mixture vented to the atmosphere. Vapor tightness of the tank can influence the evaporation rate. The moving molecule in the vapor state tends to keep going if there is no restraining force such as a tight shell or roof.

Different causes of emissions are associated with a floating-roof tank. These causes are known as wicking and wetting. Wicking emissions are caused by the capillary flow of the liquid between the outer side of the sealing ring and the inner side of the tank wall. The wetting emission results when the floating roof moves towards the bottom of the tank during emptying and leaves the inner tank shell covered with a film of liquid, which evaporates when exposed to the atmosphere.

Hydrocarbon Emissions From Floating-Roof Tanks

The American Petroleum Institute (1962b) has published a method of determining the standing (wicking) and withdrawal (wetting) evaporation emissions associated with floating roof-tanks. The method is applicable to tanks in crude oil as well as gasoline service. It is based upon field test data for the standing emission, and laboratory data for the withdrawal emission. The correlation presents factors under many combinations of tank construction, type and condition of roof seal, and color of tank paint. Parameters include range of vapor pressure from 2 to 11 psia true vapor pressure, 4 to 16 mph average wind velocity, and 20- to 200-foot-diameter tanks.

The standing storage emission is determined from Table 168. It is the product of emission factor L_f obtained from the graph and corresponding factors obtained from the table. One must know the following factors to find the value of the standing storage emissions: (1) Type of product stored, (2) Reid vapor pressure, (3) average storage temperature, (4) type of shell construction, (5) tank diameter, (6) color of tank paint, (7) type of floating roof, (8) type and condition of seal, and (9) average wind velocity in area.

The standing storage emission formula is given as

$$Ly = k_t D^{1.5} \left(\frac{P}{14.7 - P}\right)^{0.7} V_w^{0.7} k_s k_c k_p \qquad (127)$$

where Ly = standing storage evaporation emission, bbl/yr

k_t = tank factor with values as follows:

0.045 for welded tank with pan or pontoon roof, single or double seal;

0.11 for riveted tank with pontoon roof, double seal;

0.13 for riveted tank with pontoon roof, single seal;

0.13 for riveted tank with pan roof, double seal;

0.14 for riveted tank with pan roof, single seal (double deck roof is similar to a pontoon roof);

D = tank diameter, ft [for tanks larger than 150 ft in diameter use $150^{1.5}$ (D/150)]

P = true vapor pressure of stock at its average storage temperature, psia

V_w = average wind velocity, mph

k_s = seal factor:

1.00 for tight-fitting seals (typical of modern metallic or tube seals)

1.33 for loose-fitting seals

k_c = stock factor:

1.00 for gasoline stocks

0.75 for crude oils

k_p = paint factor for color of shell and roof:

1.00 for aluminum or light grey

0.90 for white.

Actual standing storage emissions of petroleum hydrocarbons from tanks equipped with seals in good operation should not deviate from the estimated emissions determined by this equation by more than $\pm$ 25 percent. The actual emissions, however, can exceed the calculated amount by two or three times for a seal in poor condition.

The seal length can be expressed in terms of tank diameter because the two are directly proportional to each other. The actual emission is not di-

Table 168. STANDING STORAGE EVAPORATION EMISSIONS FROM FLOATING-ROOF TANKS: L_y (LOSS IN bbl/yr) = L_f (LOSS FACTOR FROM FIGURE 437) TIMES MULTIPLYING FACTOR (FROM THIS TABLE: American Petroleum Institute, 1962b)

Multiplying factors apply to L_f	Welded tanks				Riveted tanks															
	Pan or pontoon roof				Pan roof								Pontoon roof							
	Single or double seal				Single seal				Double seal				Single seal				Double seal			
	Modern		Old[a]		Modern		Old[a]		Modern		Old[a]		Modern		Old[a]		Modern		Old[a]	
	Tank paint[b]		Tank paint		Tank paint		Tank paint		Tank paint		Tank paint		Tank paint		Tank paint		Tank paint		Tank paint	
	Lt grey	White	Lt grey	White	Lt grey	White	Lt grey	White	Lt grey	White	Lt grey	White	Lt grey	White	Lt grey	White	Lt grey	White	Lt grey	White
Gasoline	1.0	0.90	1.33	1.20	3.2	2.9	4.2	3.8	2.8	2.5	3.8	3.4	2.8	2.5	3.8	3.4	2.5	2.2	3.3	3.0
Crude oil	0.75	0.68	1.0	0.90	2.4	2.2	3.1	2.8	2.1	1.9	2.8	2.5	2.1	1.9	2.8	2.5	1.9	1.7	2.5	2.2

[a]Seals installed before 1942 are classed as old seals.
[b]Aluminum paint is considered light grey in loss estimation.

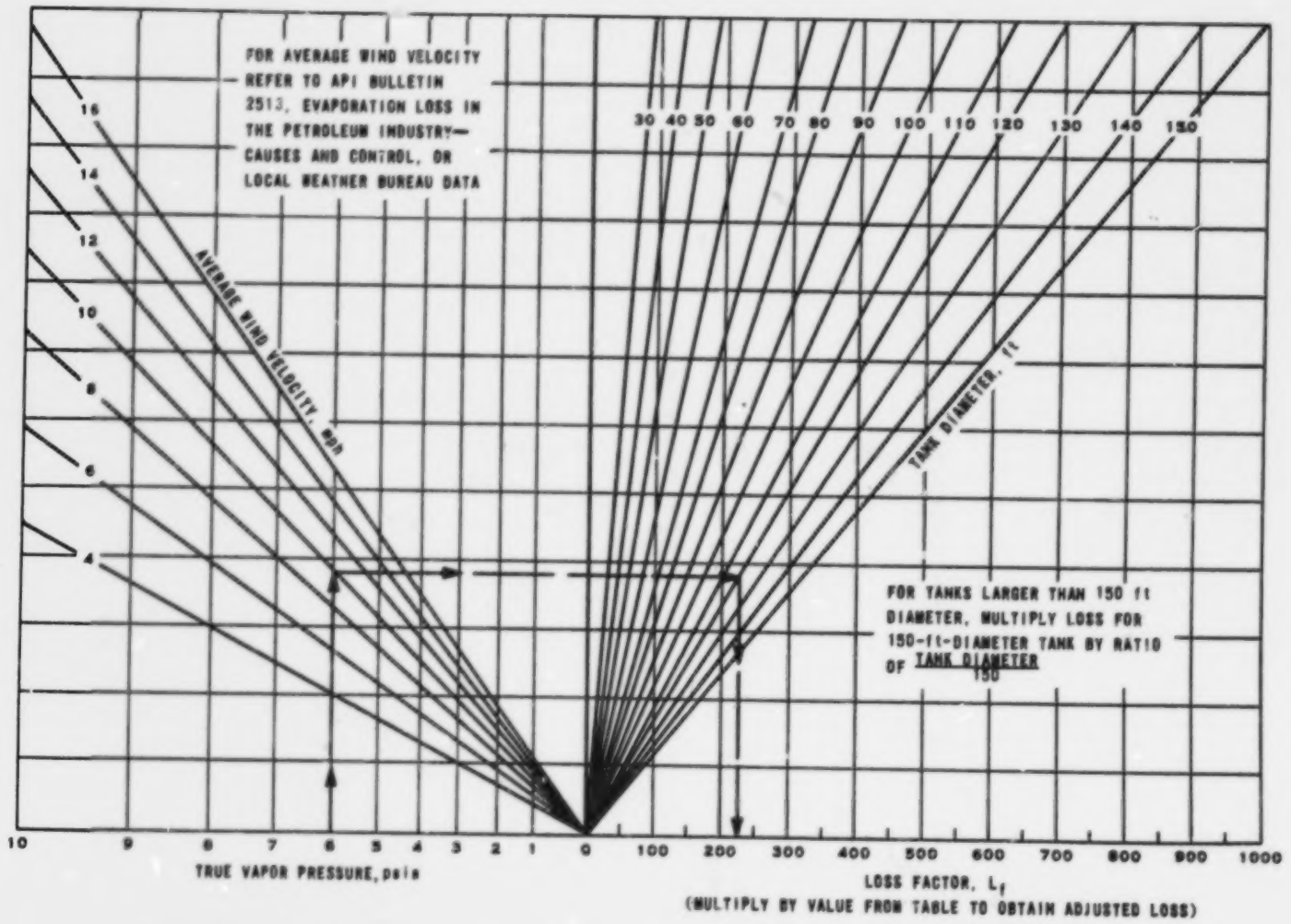

FOR AVERAGE WIND VELOCITY REFER TO API BULLETIN 2513, EVAPORATION LOSS IN THE PETROLEUM INDUSTRY—CAUSES AND CONTROL, OR LOCAL WEATHER BUREAU DATA
AVERAGE WIND VELOCITY, mph
TANK DIAMETER, ft
FOR TANKS LARGER THAN 150 ft DIAMETER, MULTIPLY LOSS FOR 150-ft-DIAMETER TANK BY RATIO OF TANK DIAMETER / 150
TRUE VAPOR PRESSURE, psia
LOSS FACTOR, L_f
(MULTIPLY BY VALUE FROM TABLE TO OBTAIN ADJUSTED LOSS)

Figure 437. Calculation of emission factor, L_f, for standing storage evaporation emissions from floating-roof tanks (see Table 168).

rectly proportional to the diameter because several other variables are involved. Items such as wind velocity and the decreased shading effect of the shell on the roof of large-diameter tanks are examples.

Emissions increase, but not directly, as the vapor pressure increases. The relationship P/(14.7 - P) correctly identifies this phenomenon, and no substantial error exists within the valid range of this correlation.

Standing storage emissions increase but do not double when the average wind velocity doubles. The 0.7 exponent applied to the wind factor fits data for average wind velocities exceeding 4 mph. No localities were recorded as having less than this 4 mph average wind velocity.

Withdrawal emissions

As product is withdrawn from a floating-roof tank, the wetted inner shell is exposed to the atmosphere. Part of the stock clinging to the inner surface drains down the shell. The remainder evaporates to the atmosphere. Tests made determined the amount of gasoline clinging to a rusty steel surface as ranging from 0.02 to 0.10 barrel of gasoline per 1,000 square feet of surface.

The withdrawal emissions are represented by the equation

$$W = 22,400\left(\frac{C}{D}\right) \qquad (128)$$

where

W = withdrawal emissions, bbl per million bbl throughout

C = 0.02 (based on barrels of clingage per 1,000 ft^2 of shell surface)

D = tank diameter, ft

Withdrawal emissions for gunited tanks can be significant. Laboratory data indicated a factor of C = 2.0. Since withdrawal emissions counter standing storage emissions, a factor C = 1.0 is recommended for gunite-lined tanks storing gasoline.

Application of results

The emissions from floating-roof tanks can be estimated from Table 168. Necessary data include: Tank diameter; color of tank paint; type of tank shell, roof, and seal; Reid vapor pressure and average temperature of stored product; and the average wind velocity at tank site.

The true vapor pressure, P, can be obtained from vapor pressure charts by the use of data in Figures 438 and 439. To use these charts, one must know the Reid vapor pressure of the stock. Figure 438 is used for gasoline or other finished stocks. The value of S (slope of the ASTM distillation curve at 10 percent evaporated) can be estimated by using suggested values given in a note of the chart. The value of S is zero for a single component stock. The vapor pressure chart, Figure 439, should be used for crude oils. This chart is intended for stabilized crudes that have not been subjected to extreme weathering or mixed with light oils.

The average stock temperatures should be used in these vapor pressure determinations.

Withdrawal emissions should be added to the standing storage emissions when gunited tanks are encountered.

Hydrocarbon Emissions From Low-Pressure Tanks

Low-pressure tanks are used to store petroleum stocks of up to 30 pounds RVP* with relief valve settings of 15 psig. The American Petroleum Institute's Evaporation Loss Committee (1962c) recommends a theoretical approach to emission calculations from tanks such as these. Insufficient data are available to establish any accurate correlation with actual field conditions.

Application of the following equation indicates the theoretical pressure (P_2) required to prevent breathing losses:

$$P_2 = 1.1\,(P_a + P_1 - p_1) - (P_a - p_2) \qquad (129)$$

where

P_2 = gage pressure at which pressure vent opens, psig

P_a = atmospheric pressure

P_1 = gage pressure at which vacuum vent opens, psig

p_1 = true vapor pressure at 90°F minimum liquid surface temperature, psia

p_2 = true vapor pressure at 100°F maximum liquid surface temperature, psia.

This equation is applicable only when the vapor pressure at minimum surface temperature (P_1) is less than the absolute pressure ($P_1 + P_a$) at which the vacuum vent opens. Air always exists in the vapor space under a condition such as this. Figure 440 is a plot of equation 129. The pressure required to eliminate breathing emissions from products ranging up to 17.5 psia TVP† at 100°F storage temperature and 14.7 atmospheric pressure can be determined from this curve. The gage pressure at which the vacuum vent opens

*RVP refers to Reid vapor pressure as measured by ASTM D 323-58 Standard Method of Test for Vapor Pressure of Petroleum Products (Reid Method).

†TVP refers to true vapor pressure.

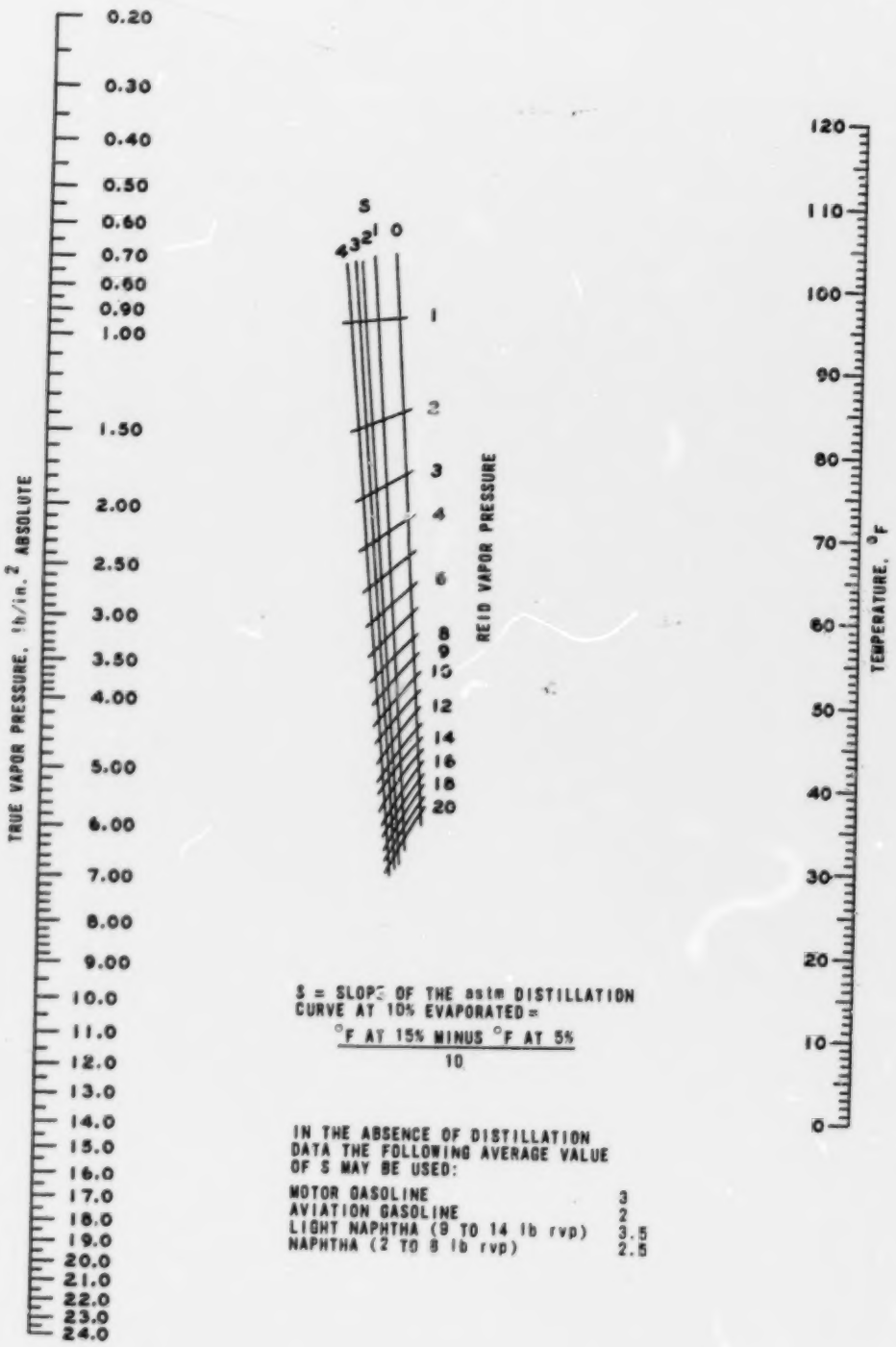


Figure 438. Vapor pressures of gasolines and finished petroleum products, 1 lb to 20 lb RVP. Nomograph drawn from data of the National Bureau of Standards (American Petroleum Institute, 1962b).

(P_1) is zero for this curve. The values of p_1 and p_2 were obtained from Figure 438. Since higher vapor pressure stocks have a smaller distillation slope (s), a range of distillation slopes was used.

The altitude of the storage vessel's location affects the required storage pressure. Proper adjustments for various altitudes can be made by substituting the proper atmospheric pressure (P_a) in equation 129. Table 169 lists atmospheric pressures at various altitudes.

Some pressure tanks must be operated at relatively low pressures--some by design, others because of corroded tank conditions. Pressure settings from zero to 2.5 psig are believed to decrease the breathing emissions from 100 percent to zero percent, depending upon the vapor pressure of the material stored. This is shown in Figure 441. Each additional increment of pressure reduces the breathing emissions by a progressively smaller amount. Boiling emissions occur when the true vapor pressure of the liquid exceeds the pressure

Figure 439. Vapor pressures of crude oil (American Petroleum Institute, 1962b).

Table 169. ATMOSPHERIC PRESSURE AT ALTITUDES ABOVE SEA LEVEL (American Petroleum Institute, 1962c)

Altitude, ft	Pressure, psia
1,000	14.17
2,000	13.66
3,000	13.17
4,000	12.69
5,000	12.23

vent setting. If this vapor pressure equals or exceeds the absolute pressure ($P_1 + P_a$) at which the tank vent opens, air is kept out of the tank. The absolute tank pressure then equals the vapor pressure of the liquid at the liquid surface temperature. The storage pressure required to prevent boiling is

$$P_2 = p_2 - P_a \qquad (130)$$

This equation is also indicated in Figure 440. These minimum pressure requirements have

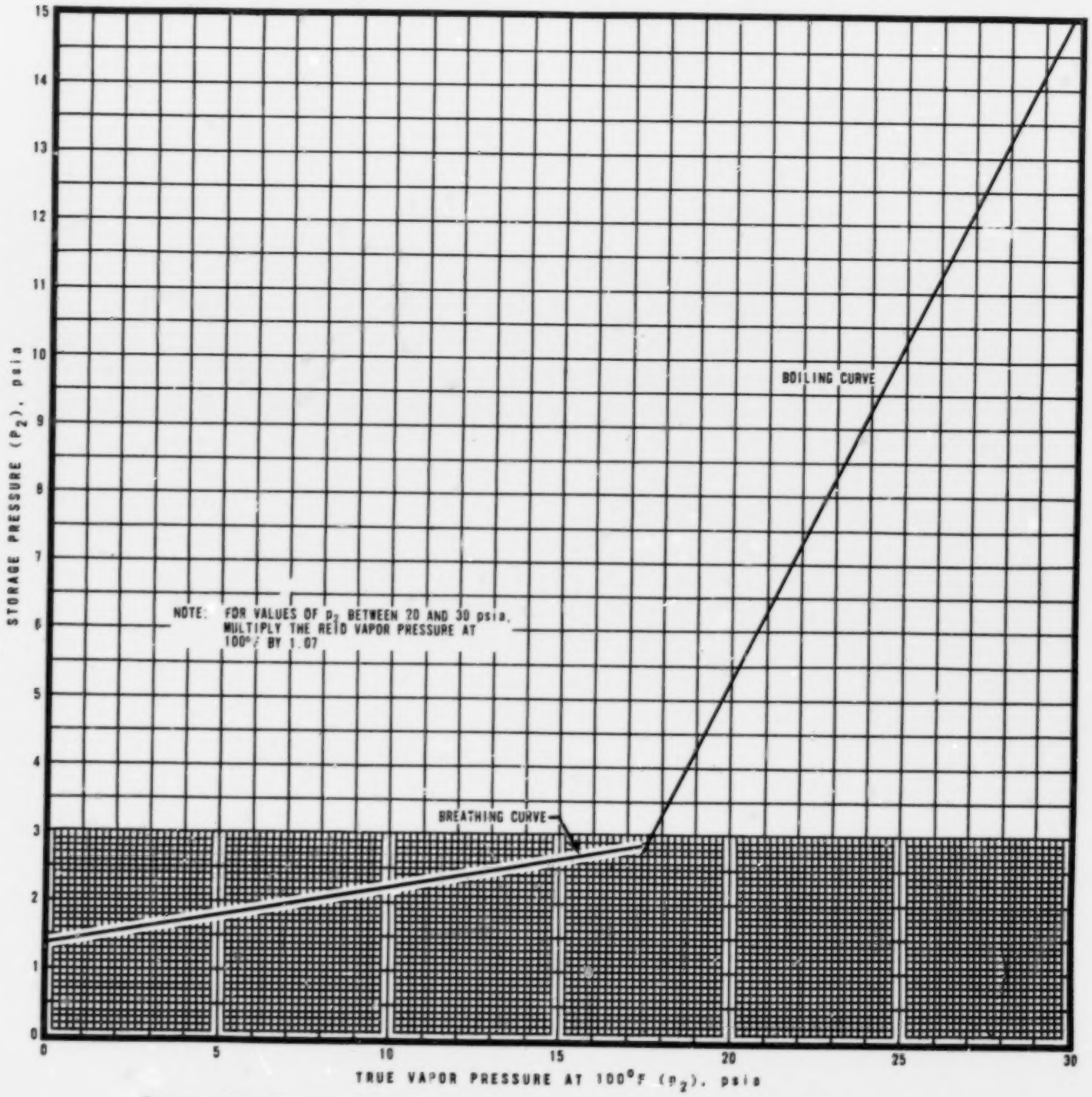


Figure 440. Storage pressure required to eliminate breathing and boiling losses. For values of p_2 between 20 and 30 psia, multiply the Reid vapor pressure at 100°F by 1.07 (American Petroleum Institute, 1962c).

proved adequate to prevent boiling emissions under usual storage conditions. The true vapor pressure at 100°F can be obtained from Figure 438 up to 20 pounds RVP. In the range of 20 to 30 RVP, P_2 is approximately 7 percent higher than the RVP at 100°F.

A filling or working emission occurs if the tank pressure exceeds the vent setting. During the initial stage of filling, compression of the air-hydrocarbon mixture with some condensation of vapor takes place if the tank pressure is less than the pressure vent setting. This condensation maintains a fairly constant hydrocarbon partial pressure. Thus, a certain fraction of the vapor space can be filled with a liquid before the tank pressure increases above the vent setting. As filling continues, the total pressure increases to the pressure at which the relief valve opens. Venting to the atmosphere occurs beyond this point. If there is no change in temperature of the liquid or vapor during the filling

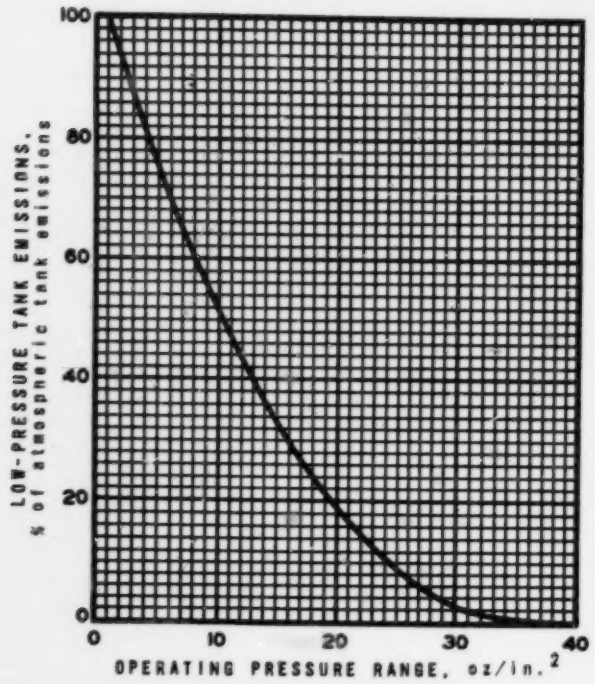


Figure 441. Relationship for estimating motor gasoline breathing emissions from tanks operating at less than the recommended 2.5-psig vent setting (American Petroleum Institute, 1962c).

period, the liquid entering the tank displaces to the atmosphere an equal volume of vapors.

The total emissions depend upon the capacity of the vapor space of the tank. Since the temperature changes as condensation occurs, the rates of filling and emptying can also affect the vapor emissions. These variables increase the difficulty of determining the actual emissions. In order that theoretical emissions can be calculated, two assumptions are made:

1. Equilibrium exists between the hydrocarbon content in the vapor and liquid phases under given temperature and pressure conditions.

2. Filling begins at slightly below atmospheric pressure.

The following equation can then be derived:

$$F_v = \frac{3\, p_v\, (P_a - P_1 - p_v)}{100\, (P_a + P_2 - p_v)} \qquad (131)$$

where

F_v = working emissions, % of volume pump

p_v = true vapor pressure at liquid temperature, psia

P_a = atmospheric pressure, psia

P_1 = gage pressure at which vacuum vent opens, psig

P_2 = gage pressure at which pressure vent opens, psig.

This calculated emission is correct on the assumption that the vapor pressure of the liquid at its surface temperature and the vapor space temperature are the same at the start and end of filling. The emissions, expressed as a percentage, are reduced to the extent that the tank is not completely filled.

Obtaining the true liquid-surface temperature is difficult. Thus, the value of p_v is based upon the average main body temperature of the liquid. As a result of possible variables, the required pressure to prevent breathing emissions from low-pressure tanks, as found by Figure 440, should be considered to have no pressure rise available to decrease the working emissions. The working emissions can be found in the same manner as for an atmospheric tank.

Figure 442 is based upon equation 131, except that the emission values are plotted for various vapor pressures and pressure vent settings greater than atmospheric pressure. The straight line gives theoretical filling emissions from tanks with vents set at only slightly greater than atmospheric pressure. The values are representative for 12 turnovers per year normally experienced with this type of low-pressure storage.

Hydrocarbon Emissions From Fixed-Roof Tanks

A revised method of determining hydrocarbon emissions from fixed-roof tanks has been published by the American Petroleum Institute (1962a). Various test data were evaluated and correlated to obtain methods of estimating breathing emissions and filling and emptying (working) emissions from fixed-roof storage tanks. The method is applicable to the full range of petroleum products, from crude oil to finished gasoline. Data were considered only for tanks with tight bottoms, shells, and roofs. All tank connections were assumed to be vapor tight and liquid tight. Of 256 separate tests recorded and screened, 178 were found acceptable for correlation. A limited number of factors were definitely found to establish a correlation. The following factors were applied in the correlation:

1. True vapor pressure, P, at storage conditions, in pounds per square inch absolute (if temperature of the liquid was not available, a temperature 5°F above average atmospheric temperature was selected);

2. tank diameter, D, in feet;

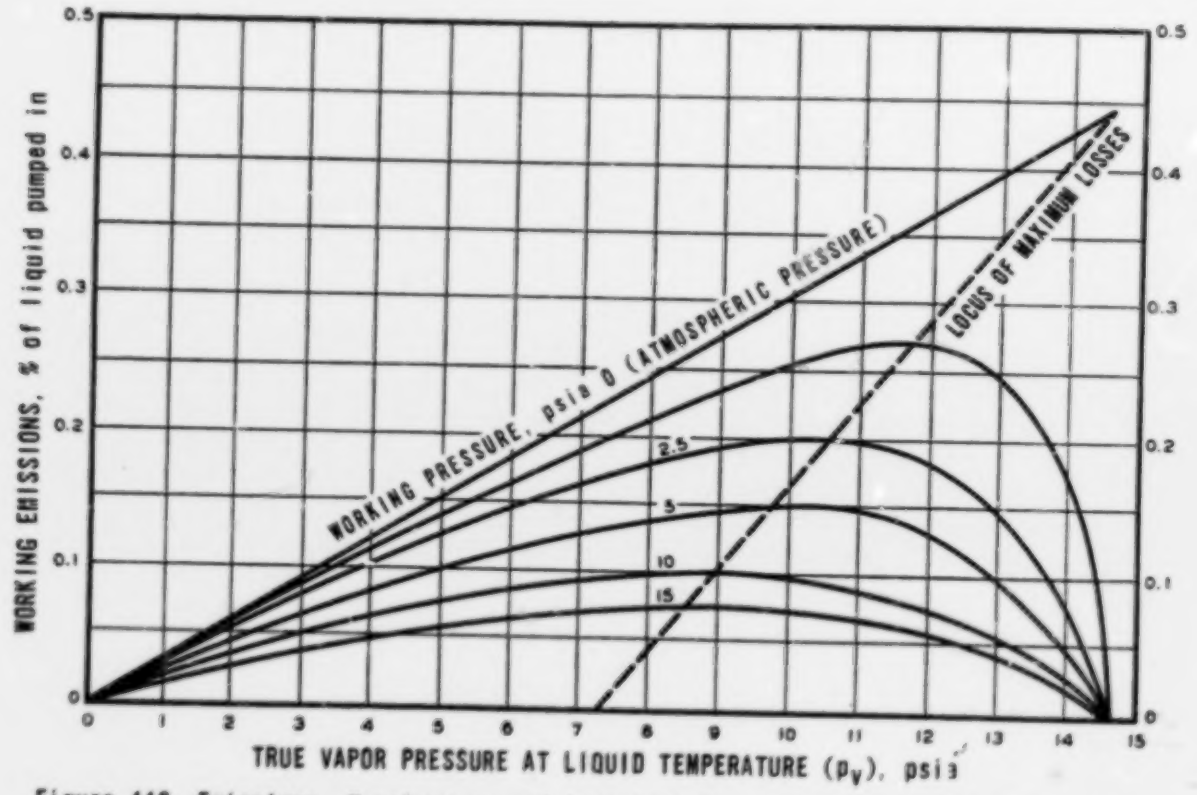


Figure 442. Emissions, % volume pumped into tank for various vent settings. ΔP is the difference between the pressure vent setting and the pressure required to prevent breathing loss (American Petroleum Institute, 1962c).

3. average tank outage, H, in feet (outage involves height of the vapor space and includes an allowance for the roof);

4. average daily ambient temperature change, T, in degrees Fahrenheit, as reported by the U.S. Weather Bureau for area where tank is located;

5. paint factor F_p (vessels with white paint in good condition have a factor of unity).

A correlation applicable to tanks with diameters of 20 feet or larger was developed:

$$L_y = \frac{24}{1,000}\left(\frac{P}{14.7 - P}\right)^{0.68} D^{1.73} H^{0.51} T^{0.50} F_p \qquad (132)$$

where

L_y = breathing emissions, bbl/yr

P = true vapor pressure at bulk liquid temperature, psia, from Figure 438. If the average liquid body temperature is not available, it may be estimated at 5°F above average ambient temperature

D = tank diameter, ft

H = average outage, ft. This value includes correction for roof volume. A cone roof is equal in volume to a cylinder with the same base diameter of the cone and one-third the height of the cone

T = average daily ambient temperature change, °F

F_p = paint factor (see Table 170).

Smaller diameter tanks require a modification of equation 132. Observed emissions were less than calculated emissions for tanks of less than 30 feet diameter. If an adjustment factor, as indicated in Figure 443, is applied to the calculated emissions from equation 132, the correlation between observed and calculated data becomes more exact. By combining the adjustment factor with the tank diameter factor, a final equation is

$$L_y = \frac{24}{1,000}\left(\frac{P}{14.7 - P}\right)^{0.68} D^{1.73} H^{0.51} T^{0.50} F_p C \qquad (133)$$

where

C = an adjustment factor for small-diameter tanks, determined from Figure 443. For

Table 170. PAINT FACTORS FOR DETERMINING EVAPORATION EMISSION FROM FIXED-ROOF TANKS
(American Petroleum Institute, 1962a)

Tank color		Paint factor	
Roof	Shell	Paint in good condition	Paint in poor condition
White	White	1.00	1.15
Aluminum[a]	White	1.04	1.18
White	Aluminum[a]	1.16	1.24
Aluminum[a]	Aluminum[a]	1.20	1.29
White	Aluminum[b]	1.30	1.38
Aluminum[b]	Aluminum[b]	1.39	1.46
White	Gray	1.30	1.38
Light gray	Light gray	1.33	1.38
Medium gray	Medium gray	1.46	1.38

[a]Specular.
[b]Diffuse.

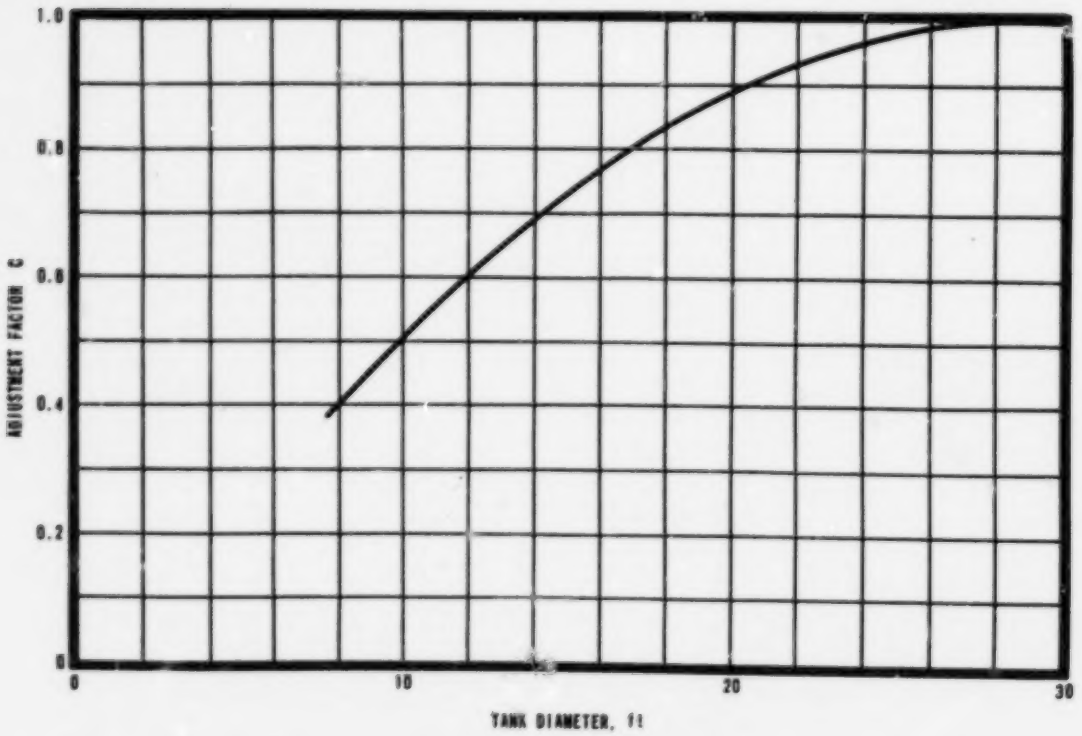


Figure 443. Adjustment factor for small-diameter tanks (American Petroleum Institute, 1962a).

tanks 30 feet or more in diameter, use a factor = 1. The breathing emissions from fixed-roof tanks can also be estimated from Figure 444, as well as from equation 133.

The working emissions include two phases of storage: (1) The filling emissions under which vapors are displaced by incoming liquid, and (2) the emptying emissions, which draw in fresh air and thus allow additional vaporization to take place.

Variables considered in determining this loss are true vapor pressure, throughput, and tank turnovers, which yield the equation:

$$F = \left(\frac{3\ PV}{10,000}\right) K_t \qquad (134)$$

where

F = working loss, bbl

EXAMPLE:
T = 16°F
F_p = 1.33
H = 23 Feet
P = 5.8 psia
D = 100 Feet
L_y = 1350 barrels per year

Tank Color		Paint Factor, F_p	
Roof	Shell	Paint in Good Condition	Paint in Poor Condition
white	white	1.00	1.15
aluminum (specular)	white	1.04	1.18
white	aluminum (specular)	1.16	1.24
aluminum (specular)	aluminum(specular)	1.20	1.29
white	aluminum (diffuse)	1.30	1.38
aluminum (diffuse)	aluminum (diffuse)	1.39	1.46
white	gray	1.30	1.38
light gray	light gray	1.33	—
medium gray	medium gray	1.46	—

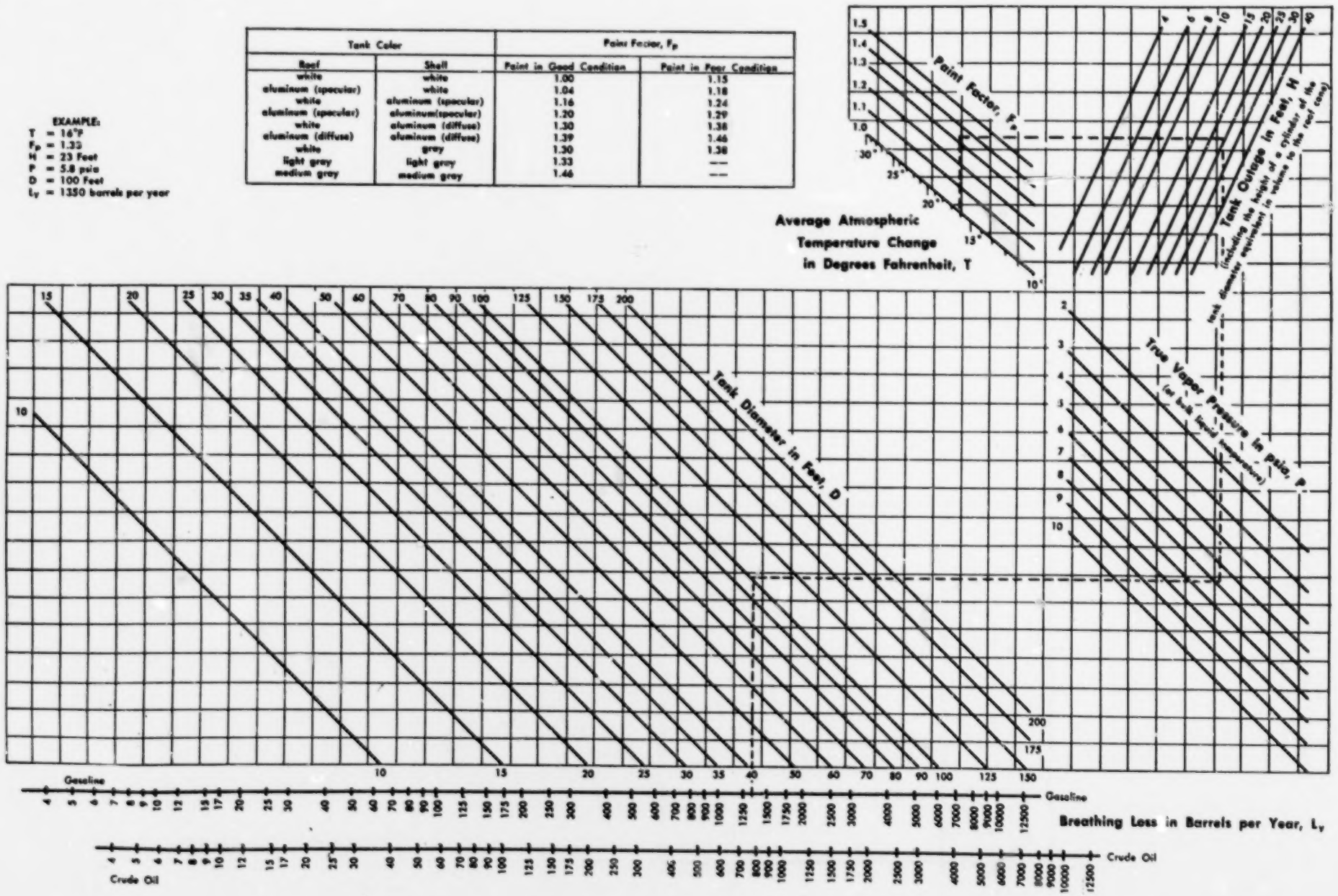

Paint Factor, F_p
Average Atmospheric Temperature Change in Degrees Fahrenheit, T
Tank Outage in Feet, H
(including the height of a cylinder of the tank diameter equivalent in volume to the roof cone)
True Vapor Pressure in psia, P
(at bulk liquid temperature)
Tank Diameter in Feet, D
Gasoline
Crude Oil
Breathing Loss in Barrels per Year, L_y

Figure 444. Breathing emissions of gasoline and crude oil from fixed-roof tanks (American Petroleum Institute, 1962a).

P = true vapor pressure at storage temperatures, psia (if these temperature data are not available, estimation of 5°F above average ambient temperature is satisfactory)

V = volume of liquid pumped into tank, bbl

K_t = turnover factor determined from Figure 445.

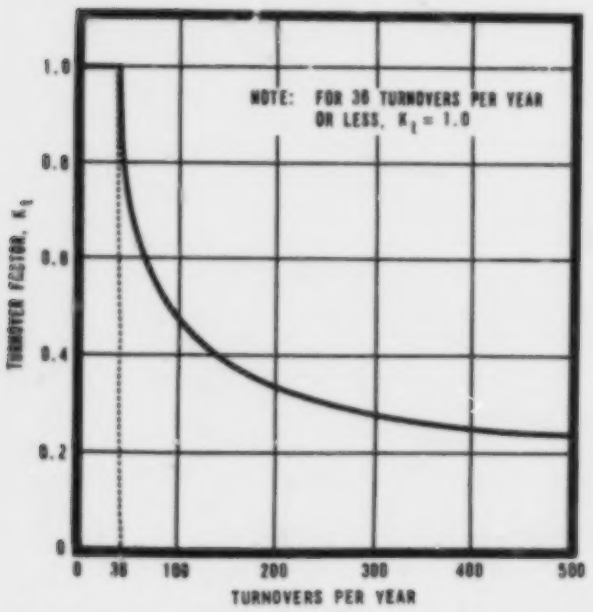


Figure 445. Effect of turnover on working emissions. For 36 or less turnovers per year, $K_t = 1.0$ (American Petroleum Institute, 1962a).

By using equation 134, a nomograph has been developed in Figure 446 showing the working emissions of gasoline and crude oil from fixed-roof tanks. Limited data resulted in the committee's using the same formula for crude oil breathing emissions as for gasoline breathing emissions with an applied adjustment factor K_c. This approach is based upon an assumption that the emissions from crude oil storage vary in the same manner as the emissions from gasoline storage, calculated from variables in equation 132. The adjustment factor, K_c, represents the ratio between the respective emissions. The true vapor pressure of crude oil must be determined from Figure 439. This figure applies to stabilized crude oil only. The breathing emission factor of 0.58 results in part from slower convective movement. This is true in the case of a liquid surface less volatile than the body of the liquid. In considering the working emissions from crude oil storage, however, filling cycles are normally less frequent than daily breathing cycles are. Thus more crude oil evaporates between cycles, creating a more saturated vapor space. The action of filling causes fresh liquid to move to the surface. A factor somewhere between 0.58 and unity appears feasible. A review of the scattered data available supports a factor of 0.75. Equation 134 then becomes

$$F_{co} = \left(\frac{2.25\,PV}{10,000}\right) K_t \qquad (135)$$

where

F_{co} = working emissions for crude oil, bbl

P = true vapor pressure, psia, determined from Figure 439 (again this may be estimated at 5°F higher than average ambient temperature in lieu of better data)

V = volume pumped into tank, bbl

K_t = turnover factor, determined from Figure 445.

Aerosol Emissions

Storage equipment can also cause air pollution in the form of aerosols or mists. An aerosol-type discharge is associated with storage of heated asphalt. This discharge is more predominant during filling operations. The reasons for this emission, other than basic displacement, are not thoroughly understood. Continued oxidation of the asphalt followed by condensation, or condensation of any moisture in the hot gases upon their entering the cooler atmosphere, are believed to be the primary causes of the mists. An analysis conducted during the filling operation found essentially air and water as the main components of the displaced vapor. Table 171 shows the results of this analysis. These vapors are frequently highly odoriferous.

Whenever live steam or air is added to a vessel for mixing, heating, oxidizing, or brightening, droplets or aerosols can be entrained with the discharge gases. Visible discharges, product loss, and odors can result.

Odors

The release of odors is closely related to evaporation and filling operations associated with the storage vessel. The concentration of odors is not, however, directly proportional to the amount of material released. Some relatively heavy compounds are very noticeable at dilutions of 1 to 5 ppm. These compounds are often toxic or highly malodorous and generally contain sulfur or nitrogen compounds.

Agitation, especially by means of air or live steam, will increase the release of odors to the atmosphere.

AIR POLLUTION CONTROL EQUIPMENT

Control of air pollution originating from storage vessels serves a three-fold purpose: (1) Elimination or reduction of air contaminants, (2) elimination or reduction of fire hazards, and (3) economic savings through recovery of valuable products. Methods of control include use of floating roofs, plastic blankets, spheres, variable vapor space systems, various recovery systems, and altered pumping and storage operations.

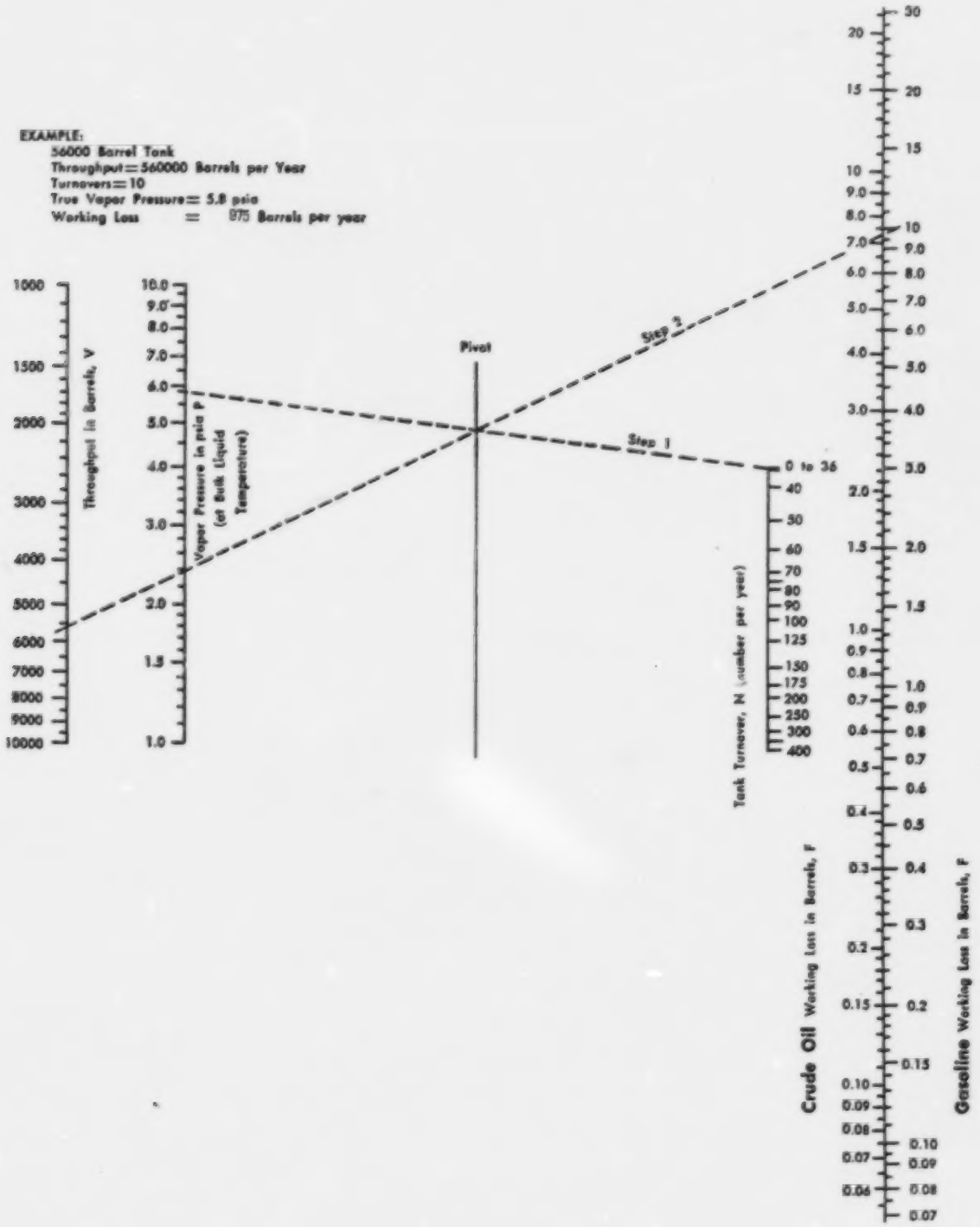

EXAMPLE:
56000 Barrel Tank
Throughput = 560000 Barrels per Year
Turnovers = 10
True Vapor Pressure = 5.8 psia
Working Loss = 875 Barrels per year
Throughput in Barrels, V
Vapor Pressure in psia P (at Bulk Liquid Temperature)
Pivot
Step 2
Step 1
Tank Turnover, N (number per year)
Crude Oil Working Loss in Barrels, F
Gasoline Working Loss in Barrels, F

Figure 446. Working emissions of gasoline and crude oil from fixed-roof tanks. The throughput is divided by a number (1,10,100,1,000) to bring it into the range of the scale. The working emission, read from the scale, must then be multiplied by the same number (American Petroleum Institute, 1962a).

Table 171. ANALYSIS OF VAPORS DISPLACED DURING FILLING 85/100 PAVING-GRADE ASPHALT INTO A FIXED-ROOF TANK[a]

Component	Volume %
Methane	Trace
Ethane	Trace
Heavy hydrocarbons (28° API gravity)	0.1
Nitrogen	67.3
Oxygen	13.0
Carbon dioxide	1.4
Water	18.2
Argon	Trace

[a]Sample was collected over 3-1/2-hour filling period, the noncondensables were analyzed by mass spectrometer. Condensable hydrocarbons were separated from the steam, and gravity and distillation curves were determined.

Seals for Floating-Roof Tanks

The principle by which a floating roof controls emissions from a volatile liquid is that of eliminating the vapor space so that the liquid cannot evaporate and later be vented. To be successful the floating roof must completely seal off the liquid surface from the atmosphere (Chicago Bridge and Iron Company, 1959). The seal for the floating roof is therefore very important. A sectional view of the sealing mechanism is shown in Figure 447. The floating section is customarily constructed about 8 inches less in diameter than the tank shell. A sealing mechanism must be provided for the remaining open annular gap. The seal also helps keep the roof centered.

Conventional seals generally consist of vertical metal plates or shoes connected by braces or pantograph devices to the floating roof. The shoes are suspended in such a way that they are forced outward against the inner tank wall. An impervious fabric bridges the annular area between the tops of the shoes contacting the tank wall and the circumference of the floating roof. To reduce emissions, a secondary seal or wiper blade has been added to the floating-roof design by extending the fabric seal or by adding a second section of fabric as shown in Figure 448. This seal remains in contact with the tank wall. Its flexibility allows it to make contact even in rivet head areas of the inner shell or in places where the shell might be slightly out of round. This improvement lowers hydrocarbon emissions further by reducing the effect of wetting and wicking associated with floating-roof tanks.

Recently, other types of sealing devices to close the annular gap have been marketed, as shown in Figure 449. These devices consist of a fabric tube that rests on the surface of liquid exposed

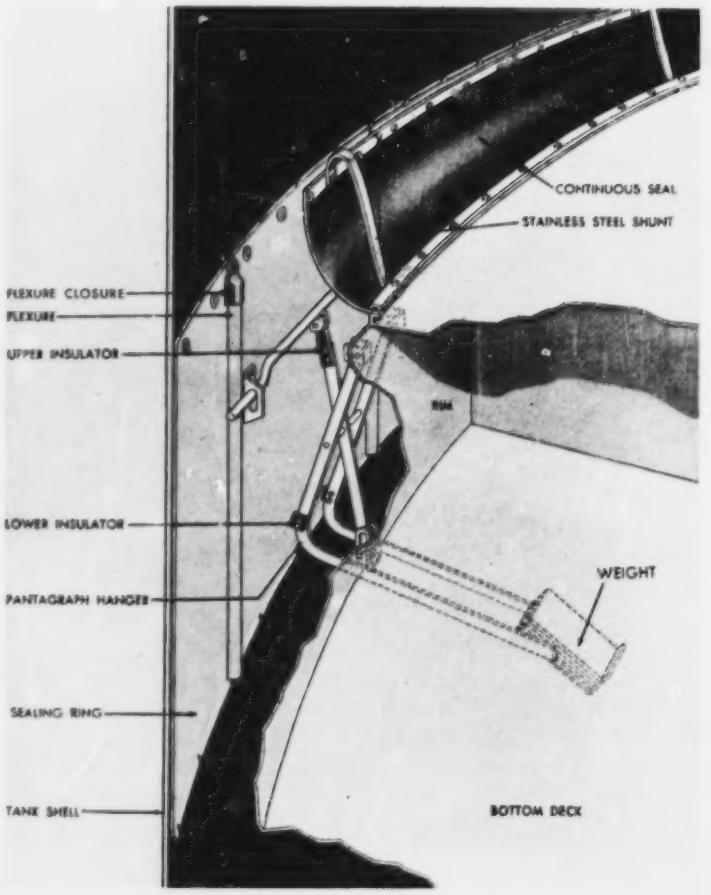


Figure 447. Sectional view of double-deck floating-roof's sealing mechanism (Chicago Bridge and Iron Co., Chicago, Ill.).

in the annular space. The fabric tube is filled with air, liquid or plastic material. The pneumatic, inflated seal is provided with uniform air pressure by means of a small expansion chamber and control valves. The sides of the tube remain in contact with the roof and inner shell. The liquid-filled tube holds a ribbed scuff band against the tank wall. The ribbed band acts as a series of wiper blades as well as a closure. All tubes are protected by some type of weather covering.

A weather covering can also be added to protect the sealing fabric of the conventional seals. The covering includes flat metal sections held in place by a metal band. The metal protects the fabric seal from the elements. When floating-roof sections are added to older tanks constructed of riveted sections, better contact of the shoes with the shell can be ensured by guniting or plastic coating the inner shell. The wetting condition of gunited walls may, however, offset the gain of better contact.

Floating Plastic Blankets

A floating plastic blanket, operates on the same principle of control as a floating roof. It is also

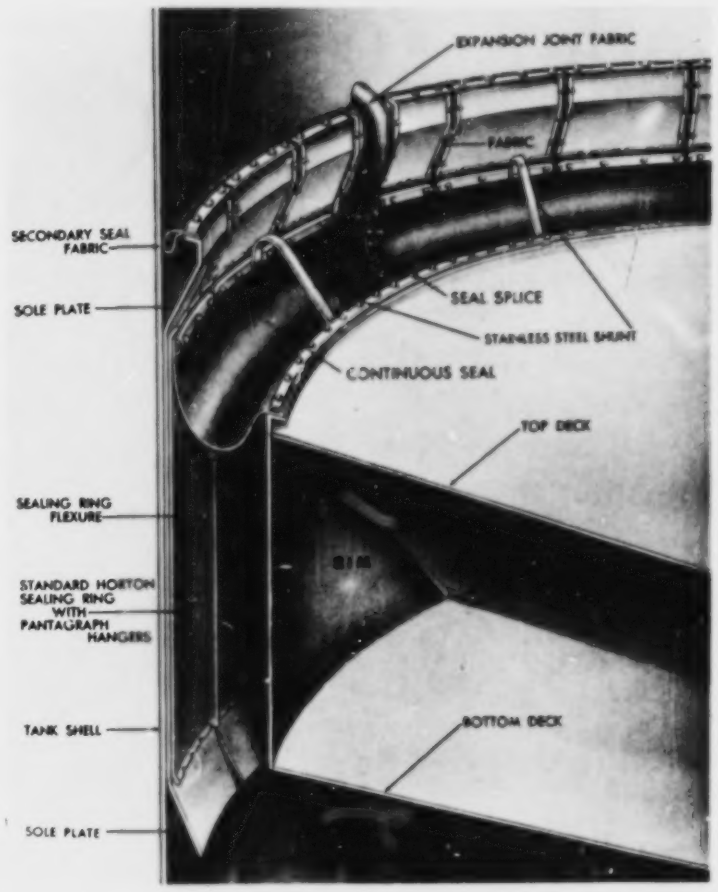


Figure 448. Secondary seals stop vapor loss from high winds on riveted tanks by sealing off the space between the tank shell and the sealing ring sole plate (Chicago Bridge and Iron Co., Chicago, Ill.).

available as a surface cover, as depicted in Figure 450. It was developed in France and has been tried principally in foreign markets (Laroche Bouvier and Company). Recent applications have been made in the United States. The blanket is usually made of polyvinyl chloride but can be made of other plastics such as polyvinyl alcohol, superpolyamides, polyesters, fluoride hydrocarbons, and so forth. The blanket's underside is constructed of a large number of floats of the same plastic material. The blanket is custom manufactured so that only a 1-inch gap remains around the periphery. A vertical raised skirt is provided at the edge of the blanket to serve as a vapor seal over the annular area. Once this area is saturated, further evaporation diminishes. The only remaining loss is gaseous diffusion. The seal is made as effective as possible by using an elastic, Z-shaped skirt.

Provisions are made in the blanket for openings fitted with vertical sleeves for measuring and sampling operations. These openings have a crosscut, flexible inner diaphragm to minimize exposure of the liquid surface. Small holes with downspouts to effect a liquid seal are used to provide drainage of any condensate from the top of the blanket. Another feature includes a stainless steel cable grid to prevent a buildup of static charges. The grid is closely attached just under the blanket in parallel lines and connected to the tank shell by a flexible conductor cable. Installation of a plastic blanket is convenient for both new and existing tanks. The blanket is made in sections and can be introduced into a tank through a manhole.

A rigid foam-plastic cover constructed of polyisocyanate foam is also available to equip small fixed-roof tanks with a floating cover. The cover is manufactured in radial sections, each equipped with a flexible neoprene seal attached on the outer edge. The sections are easily installed through roof manholes and assembled with slip-fit joints.

Plastic Microspheres

An outgrowth of application of plastic material provides another type of control mechanism. This type of control is also similar to the floating roof. A phenolic or urea resin in the shape of tiny, hollow, spherical particles has been developed by Standard Oil Company of Ohio (American Petroleum Institute, 1962d). This material has the physical properties necessary to form a foam covering over the denser petroleum products. The fluidity of the layer enables it to flow around any internal tank parts while keeping the liquid surface sealed throughout any level changes. These plastic spheres are known under their trademark names of microballoons or Microspheres. These coverings have proved to be effective controls for fixed-roof crude oil tanks. Excessive amounts of condensation or high turbulence should be avoided. The plastic foam has not proved as satisfactory for one-component liquid or gasoline products.

A 1/2-inch layer of foam has been found sufficient for crude oil where pumping rates do not exceed 4,000 barrels per hour. A layer 1 inch thick is recommended for pumping rates up to 10,000 barrels per hour. In order to overcome wall holdup in smaller tanks, it is suggested that a 1-inch layer be used regardless of pumping rates. For tanks storing gasoline, the recommended foam thickness is 2 inches for tanks up to 40 feet in diameter, and 1 inch for all larger diameter vessels.

Various methods can be used to put the foam covering on the crude oil. One method is to inject the plastic spheres with the crude oil as it is charged to the tank. Spheres are added by means of an aspirator and hopper similar to equipment used in fire-fighting foam systems. The spheres can also be added by placing the desired quantity

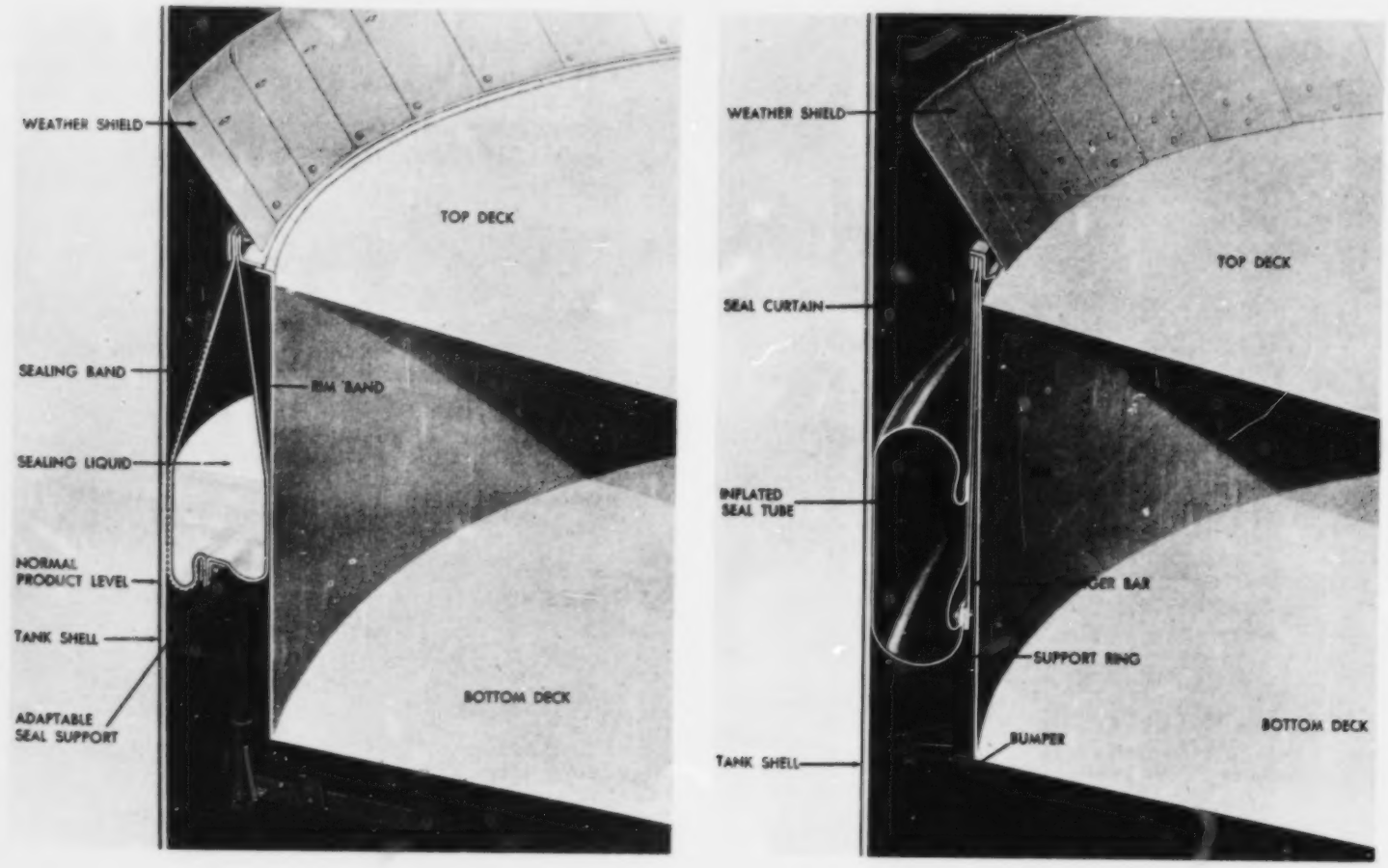


Figure 449. Sealing devices for floating-roof tanks: (upper left) Liquid-filled tube seal, (upper right) inflated tube seal, (lower left) foam-filled tube seal (Chicago Bridge and Iron Co., Chicago, Ill.)

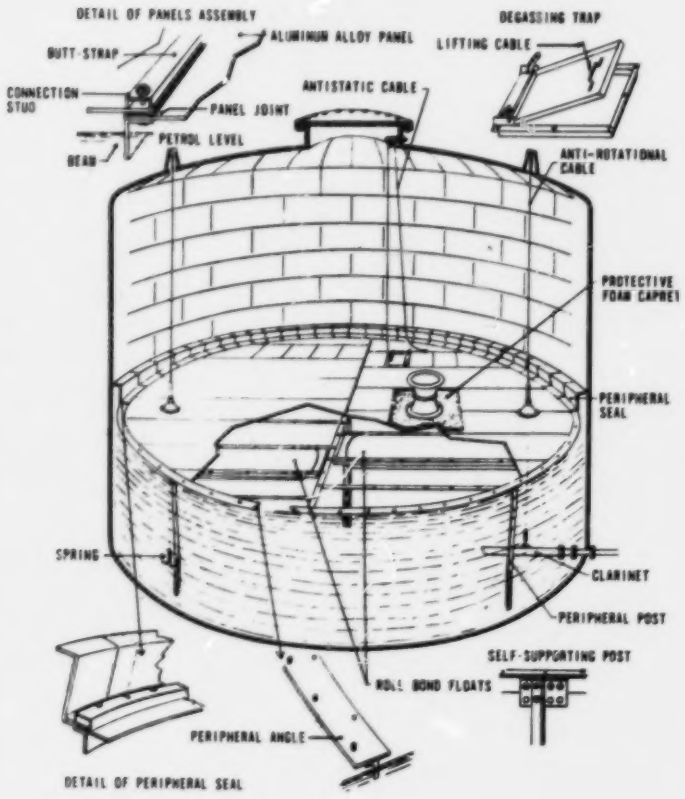


Figure 450. Fixed-roof tank with internal plastic floating blanket (Laroche Bouvier and Company, 5. Boulevard Edgar-Quinet, Colombes (Seine), France).

on the clean, dry floor of the tank just before the crude oil is charged. A wetting agent must be used when the foam covering is to be used on gasoline products. This is accomplished by slurrying the plastic spheres, wetting agent, and gasoline in a separate container. The slurry is then injected into the tank. Changes in tank operation are not necessary except for gaging or sampling. A floating-type well attached to a common-type gaging tape allows accurate measurement of the tank's contents. A sample thief with a piercing-type bottom is needed for sampling.

Protection against excessive loss of the plastic spheres is necessary because of the relative value of the foam covering. Precaution must be taken against overfilling and pumping the tank too low. Standard precautions against air entrainment in pipelines normally safeguard against the latter. Overfilling can be prevented by automatic shutoff valves or preset shutoff operations. Low-level shutoff should prevent vortices created during tank emptying. Other than loss of the foam, no trouble should be encountered if the spheres escape into process lines. The plastic material is not as abrasive as the sand particles normally found entrained in crude oil. Excessive pressures crush the spheres and the plastic settles in the water or sediment. At high temperatures, the thermo-setting resins soften, liquefy, and mix with the fuel oil, asphalt, or coke.

Vapor Balance Systems

Variable vapor space or vapor balance systems are designed to contain the vapors produced in storage. They do not achieve as great a reduction in emissions as an appropriately designed vapor recovery system does. A well-planned unit includes storage of similar or related products, and uses the advantage of in-balance pumping situations. Only the vapor space of the tanks is manifolded together in these systems. Other systems include a vapor reservoir tank that is either a lifter-roof type or a vessel with an internal diaphragm. The latter vessel can be an integrated vapor-liquid tank or a separate vaporsphere. The manifold system includes various sizes of lightweight lines installed to effect a balanced pressure drop in all the branches while not exceeding allowable pressure drops. Providing isolating valves for each tank so that each tank can be removed from the vapor balance system during gaging or sampling operations is also good practice. Excessive vapors that exceed the capacity of the balance system should be incinerated in a smokeless flare or used as fuel.

Vapor Recovery Systems

The vapor recovery system is in many ways similar to and yet superior to a vapor balance system in terms of emissions prevented. The service of this type of vapor recovery system is more flexible as to the number of tanks and products being stored. The recovery unit is designed to handle vapors originating from filling operations as well as from breathing. The recovered vapors are compressed and charged to an absorption unit for recovery of condensable hydrocarbons. Noncondensable vapors are piped to the fuel gas system or to a smokeless flare. When absorption of the condensable vapors is not practical from an economic standpoint, these vapors, too, are sent directly to the fuel system or incinerated in a smokeless flare.

The recovery system, like the vapor balance system, includes vapor lines interconnecting the vapor space of the tanks that the system serves. Each tank should be capable of being isolated from the system. This enables the tanks to be sampled or gaged without a resulting loss of vapors from the entire system. The branches are usually isolated by providing a butterfly-type valve, a regulator, or a check valve. Since the valves offer more line resistance, their use is sometimes restricted. Small

vessels or knockout pots should be installed at low points on the vapor manifold lines to remove any condensate.

In some vapor recovery systems, certain tanks must be blanketed with an inert atmosphere in order to prevent explosive mixtures and product contamination. In other, larger systems, the entire manifolded section is maintained under a vacuum. Each tank is isolated by a regulator-control valve. The valves operate from pressure changes occurring in the tank vapor space.

Because the vapor-gathering system is based upon positive net vapor flow to the terminus (suction of compressors), the proper size of the vapor lines is important. Sizing of the line, as well as that of the compressors, absorption unit, or flare, is based upon the anticipated amount of vapors. These vapors are the result of filling operations and breathing. The distance through which the vapors must be moved is also important.

Miscellaneous Control Measures

Recent tests have shown that breathing emissions from fixed-roof tanks can be reduced by increasing the storage pressure. An increase of 1 ounce per square inch was found to result in an 8 percent decrease in emissions due to breathing. Tanks operated at 2-1/2 psig or higher were found to have little or no breathing emissions. The pressure setting, however, should not exceed the weight of the roof.

A major supplier (Shand and Jurs Co.) of tank accessories offers another method of reducing breathing losses. The method is based upon the degree of saturation in the vapor space. A baffle located in a horizontal position immediately below the vent, as shown in Figure 451, directs entering atmospheric air into a stratified layer next to the top of the tank. Since this air is lighter, it tends to remain in the top area; thus, there is less mixing of the free air and any of the rich vapor immediately above the liquid surface. The top stratified layer is first expelled during the outbreathing cycle. Test data indicate a reduced surface evaporation of 25 to 50 percent.

Hydrocarbon emissions can be minimized further by the proper selection of paint for the tank shell and roof. The protective coating applied to the outside of shell and roof influences the vapor space and liquid temperatures. Reflectivity and glossiness of a paint determine the quantity of heat a vessel can receive via radiation. A cooler roof and shell also allows any heat retained in the stored material to dissipate. Weathering of the paint also influences its effectiveness. The relationship of paints in keeping tanks from warming in the sun is indicated in Table 172. Vapor space temperature reductions of 60°F have been reported. Similarly, liquid-surface temperature reductions of 3 to 11 degrees have been achieved. Data gathered by the American Petroleum Institute on hydrocarbon emissions indicate breathing emission reductions of 25 percent for aluminum over black paint and 25 percent for white over aluminum paint. All paints revert to "black body" heat absorption media in a corrosive or dirt-laden atmosphere.

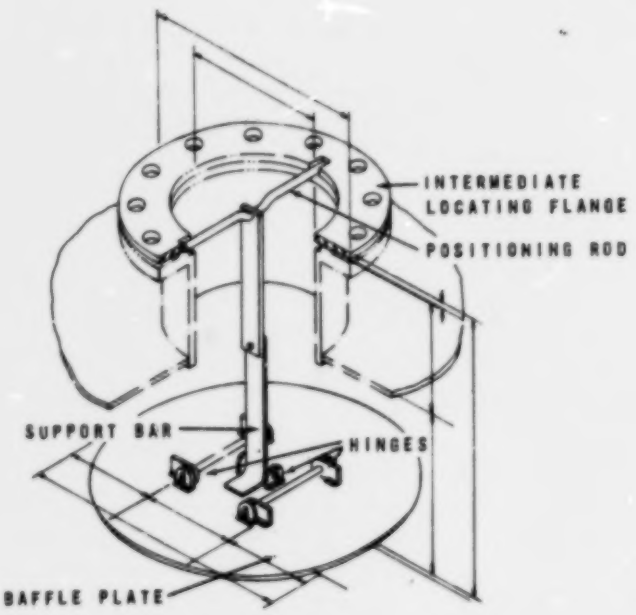


Figure 451. Air baffle (Shand and Jurs Co., Berkeley, Calif.).

Table 172. RELATIVE EFFECTIVENESS OF PAINTS IN KEEPING TANKS FROM WARMING IN THE SUN (Nelson, 1953)

Color	Relative effectiveness as reflector or rejector of heat, %
Black	0
No paint	10.0
Red (bright)	17.2
Red (dark)	21.3
Green (dark)	21.3
Red	27.6
Aluminum (weathered)	35.5
Green (dark chrome)	40.4
Green	40.8
Blue	45.5
Gray	47.0
Blue (dark Prussian)	49.5
Yellow	56.5
Gray (light)	57.0
Aluminum	59.2
Tan	64.5
Aluminum (new)	67.0
Red iron oxide	69.5
Cream or pale blue	72.8
Green (light)	78.5
Gray (glossy)	81.0
Blue (light)	85.0
Pink (light)	86.5
Cream (light)	88.5
White	90.0
Tin plate	97.5
Mirror or sun shaded	100.0

Insulation applied to the outside of the tank is one method of reducing the heat energy normally conducted through the wall and roof of the vessel. Another method of controlling tank temperatures is the use of water. The water can be sprayed or retained on the roof surface. The evaporation of the water results in cooling of the tank vapors. Increased maintenance and corrosion problems may, however, be encountered.

Storage temperatures may be reduced by external refrigeration or autorefrigeration. External refrigeration units require the circulation of the refrigerant or of the tank contents. Autorefrigeration is practical in one-component liquid hydrocarbon storage where high vapor pressure material is involved. The pressure in the tank is reduced by removing a portion of the vapor. Additional vapor is immediately formed. This flash vaporization results in lowering the temperature of the main liquid body.

Routine operations can be conduoted in such a manner as to minimize other emissions associated with storage tanks. Use of remote-level reading gages and sampling devices reduces emissions by eliminating the need to open tank gage hatches. Emissions can be further reduced by proper production scheduling to (1) maintain a minimum of vapor space, (2) pump liquid to the storage tank during cool hours and withdraw during hotter periods, and (3) maintain short periods between pumping operations.

Using wet scrubbers as control equipment for certain stored materials that are sufficiently soluble in the scrubbing media employed is both possible and practical. The scrubbers can be located over the vent when the scrubbing medium, for example, a water scrubber for aqua ammonia storage,can be tolerated in the product In other cases, the vent of one or more tanks can be manifolded so that any displaced gas is passed through a scrubbing unit before being discharged to the atmosphere. A typical example is a scrubber packed with plastic spirals that serves ketone storage vessels. The scrubbing liquid is water, which is drained to a closed waste effluent disposal system.

Properly designed condensers can be used to reduce the vapor load from tank vents in order that smaller control devices can be employed.

Masking Agents

Masking agents do not afford any degree of control of the emissions from storage equipment. The agent is employed to make the vapor or gas less objectionable. On the basis of local experience, the use of these agents is impractical, and in the long run, proper control equipment is necessary.

Costs of Storage Vessels

The installed costs of various storage vessels are indicated in Figures 452 through 459. Included are standard tank accessories such as manholes, vents, ladders, stairways, drains, gage hatches, and flanged connections.

LOADING FACILITIES

INTRODUCTION

Gasoline and other petroleum products are distributed from the manufacturing facility to the consumer by a network of pipelines, tank vehicle routes, railroad tank cars, and ocean-going tankers, as shown in Figure 460.

As integral parts of the network, intermediate storage and loading stations receive products from refineries by either pipelines or tank ve-

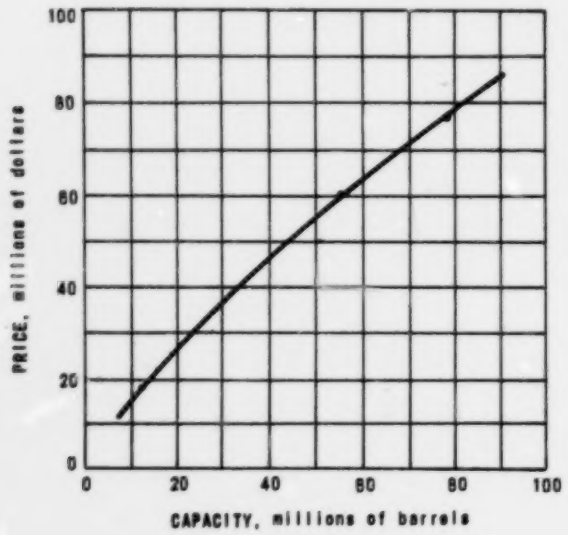


Figure 452. Installed costs of cone roof tanks.*

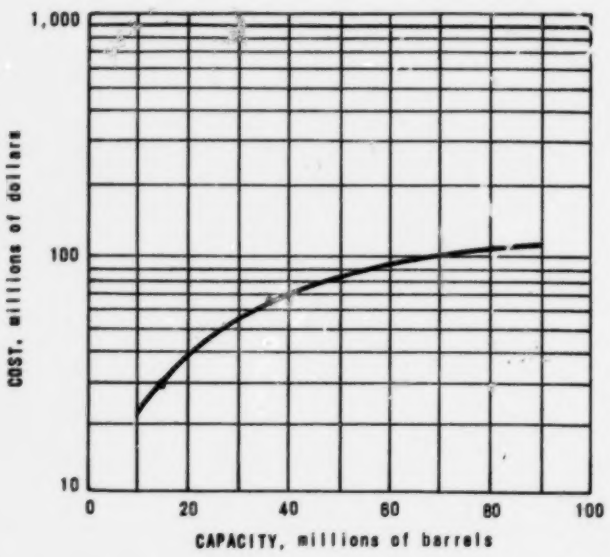


Figure 453. Installed costs of double-deck floating roof tanks.*

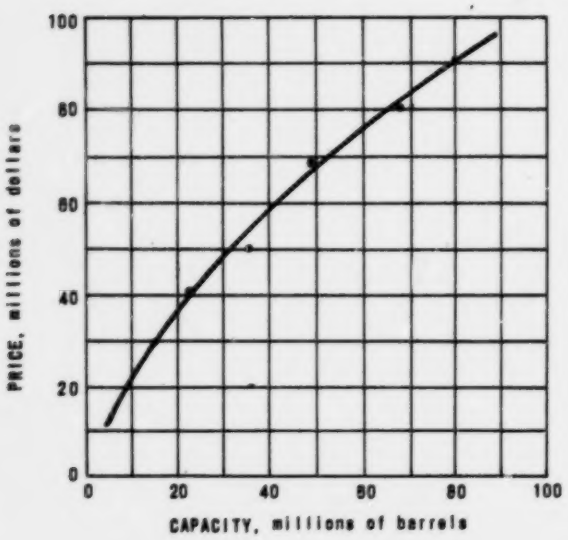


Figura 454. Installed costs of pontoon floating-roof tanks,*

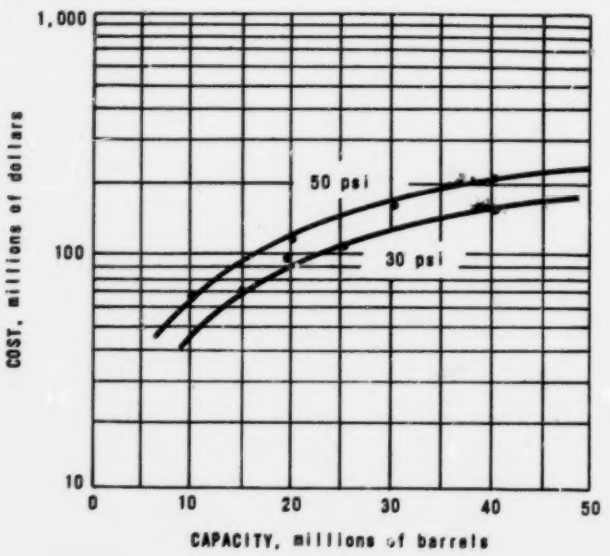


Figure 455. Installed costs of spherical pressure storage tanks.*

*Including accessories, delivered and erected (Prater and Mylo, 1961; copyrighted by Gulf Publishing Co., Houston, Texas).

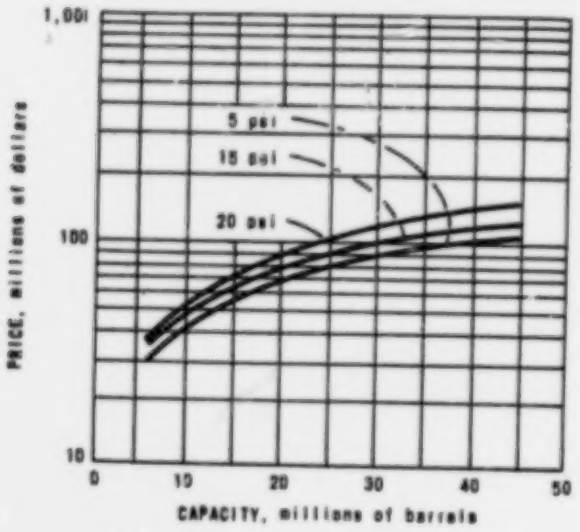


Figure 456. Installed costs of spheroids.*

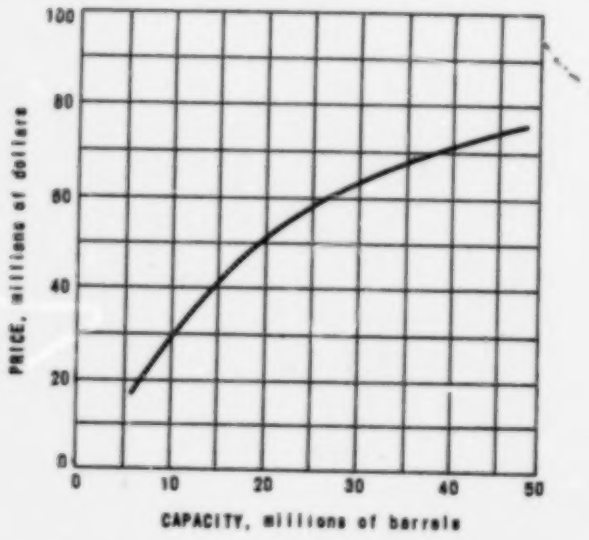


Figure 457. Installed costs of basic hemispheroids.*

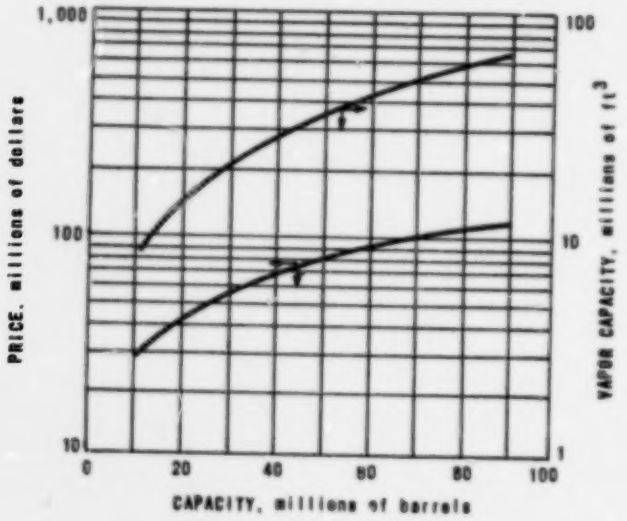


Figure 458. Installed costs of 5-ft lift expansion roof storage tanks.*

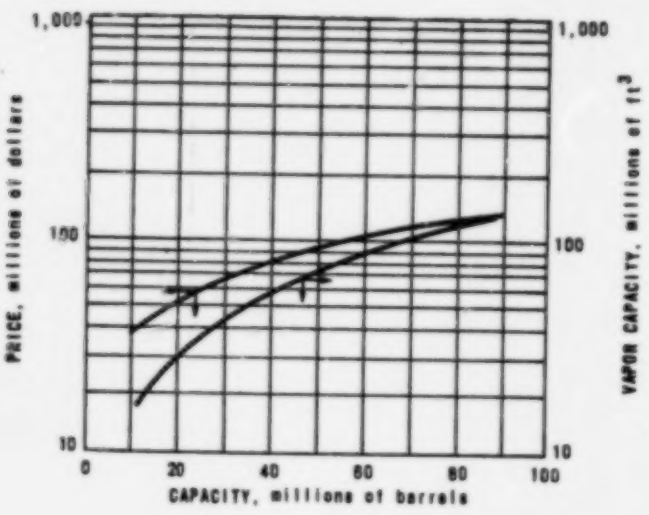


Figure 459. Installed costs of 10-ft lift expansion roof storage tanks.*

*Including accessories, delivered and erected (Prater and Hylo, 1961; copyrighted by Gulf Publishing Co., Houston, Texas).

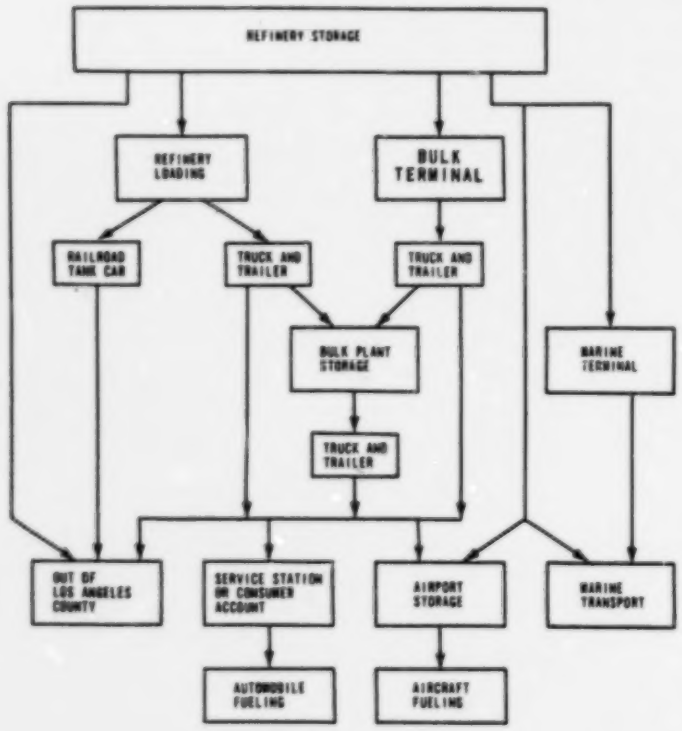


Figure 460. Representation of gasoline distribution system in Los Angeles County, showing flow of gasoline from refinery to consumer.

hicles. If the intermediate station is supplied by pipeline, it is called a bulk terminal, to distinguish it from the station supplied by tank vehicle, which is called a bulk plant. Retail service stations fueling motor vehicles for the public are, as a general rule, supplied by tank vehicle from bulk terminals or bulk plants. Consumer accounts, which are privately owned facilities operated, for example, to fuel vehicles of a company fleet, are supplied by tank vehicles from intermediate bulk installations or directly from refineries.

Gasoline and other petroleum products are loaded into tank trucks, trailers, or tank cars at bulk installations and refineries by means of loading racks. Bulk products are also delivered into tankers at bulk marine terminals.

Loading Racks

Loading racks are facilities containing equipment to meter and deliver the various products into tank vehicles from storage. Sizes of loading racks vary in accordance with the number of products to be loaded and the number of trucks or railroad tank cars to be accommodated. The loading platform may be an elevated structure for overhead filling of vehicles, that is, through the top hatches in the tank vehicle, or a ground-level facility for bottom filling. The elevated-platform structure employed for overhead filling, shown in Figures 461 and 462, is generally constructed with hinged side platforms attached to the sides of a central walkway in such a way that they can be raised when not in use. Thus, when a vehicle is positioned adjacent to the central walkway for loading, the hinged side platforms can be lowered to rest upon the top of the vehicle to provide an access to the compartment hatches. The meters, valves, loading tubes or spouts, motor switches, and similar necessary loading equipment are located on the central walkway. Bottom-loading installations are less elaborate, since the tank vehicle is filled through easily accessible fittings on the underside of the vehicles.

Marine Terminals

Marine terminals have storage facilities for crude oil, gasoline, and other petroleum products, and facilities for loading and unloading these products to and from oceangoing tankers or barges. The loading equipment is on the dock and, in modern terminals, is similar to elevated-tank vehicle-loading facilities except for size (see Figure 463). A pipeline manifold with flexible hoses is used for loading at older terminals. Marine installations are considerably larger and operate at much greater loading rates than inland loading installations.

Loading Arm Assemblies

The term loading arm assembly refers to the equipment and appurtenances at the discharge end of a product pipeline that are necessary to the filling of an individual tank vehicle or tanker compartment. Component parts may include piping, valves, meters, swivel joints, fill spouts, and vapor collection adapters. These installations are commonly called loading arms. A loading arm without provisions to control vapors displaced from the compartment during filling is shown in Figure 464.

Overhead loading arms employed for filling of tank trucks or railroad tank cars may be classified in accordance with the manner in which vertical movement of the arm is achieved, such as pneumatic, counterweighted, or torsion spring. The pneumatically operated arm is a successor to the common spring-loaded, automatic-locking arm in which the spring-loaded cylinder has been replaced by an air cylinder (see Figure 465). Bottom loading employs a flexible hose or a non-flexible, swing-type arm connected to the vehicle from ground-level pipeline termini.

Loading arms at modern marine terminals are similar in design to those used for overhead loading of tank vehicles. The tanker loading

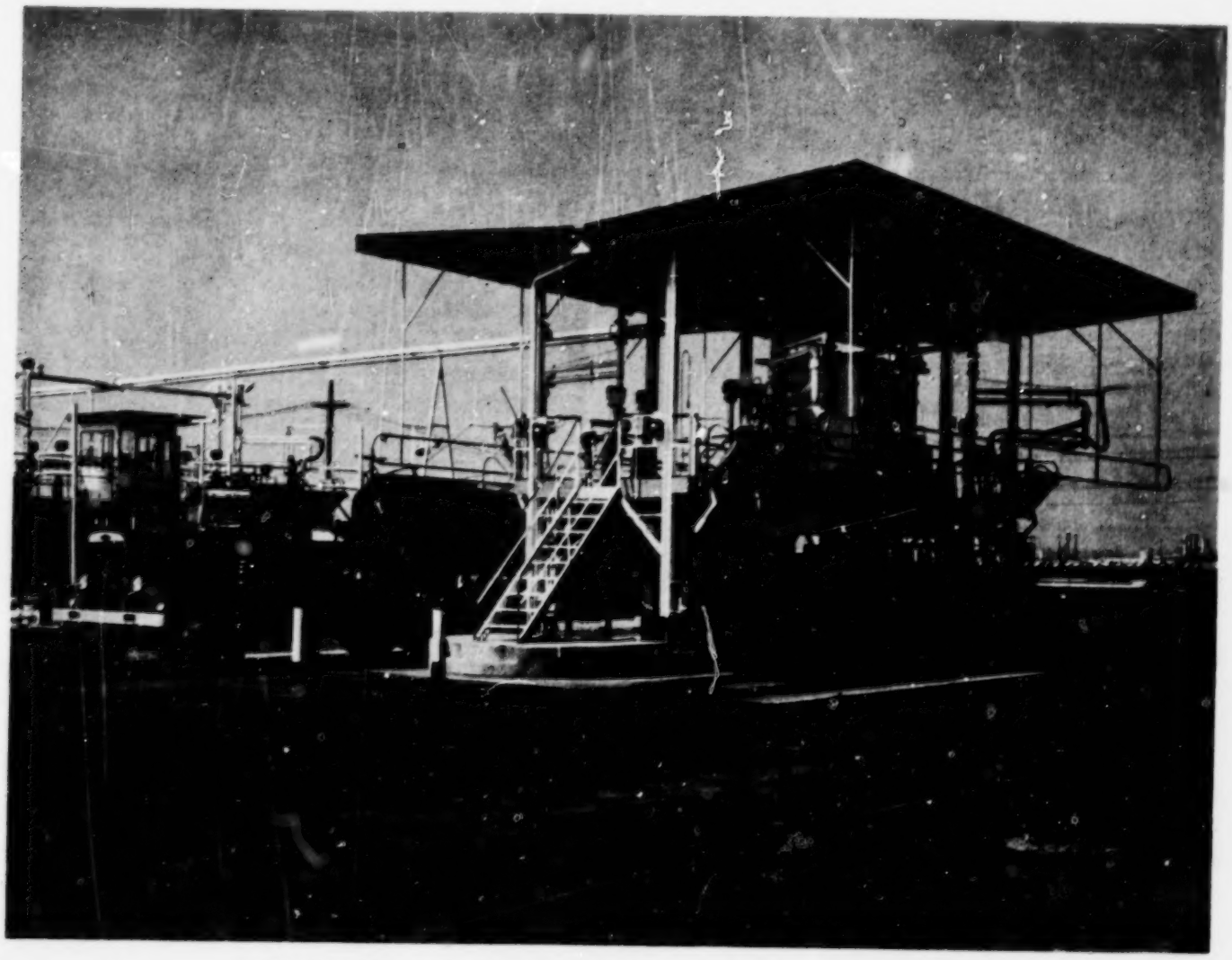


Figure 461. An overhead-controlled loading rack (Phillips Petroleum, Los Angeles, Calif.).

arms are too large for manual operation, requiring a hydraulic system to effect arm motion. Older installations use reinforced, flexible hoses to convey products from pipeline discharge manifolds to the tanker. The hoses are positioned by means of a winch or crane.

THE AIR POLLUTION PROBLEM

When a compartment of a tank vehicle or tanker is filled through an open overhead hatch or bottom connection, the incoming liquid displaces the vapors in the compartment to the atmosphere. Except in rare instances, where a tank vehicle or tanker is free of hydrocarbon vapor, as when being used for the first time, the displaced vapors consist of a mixture of air and hydrocarbon concentration, depending upon the product being loaded, the temperature of the product and of the tank compartment, and the type of loading. Ordinarily, but not always, when gasoline is loaded, the hydrocarbon concentration of the vapors is from 30 to 50 percent by volume and consists of gasoline fractions ranging from methane through hexane (Deckert et al., 1958). Table 173 shows a typical analysis of the vapors emitted during the loading of motor gasoline into tank vehicles.

The volume of vapors produced during the loading operation, as well as their composition, is greatly influenced by the type of loading or filling employed. The types in use throughout the industry may be classified under two general headings, overhead loading and bottom loading.

Overhead loading, presently the most widely used method, may be further divided into splash and submerged filling. In splash filling, the outlet of the delivery tube is above the liquid surface during all or most of the loading. In submerged filling the outlet of the delivery tube is extended to within 6 inches of the bottom and is submerged beneath the liquid during most of the loading. Splash filling generates more turbulence and therefore more hydrocarbon vapors

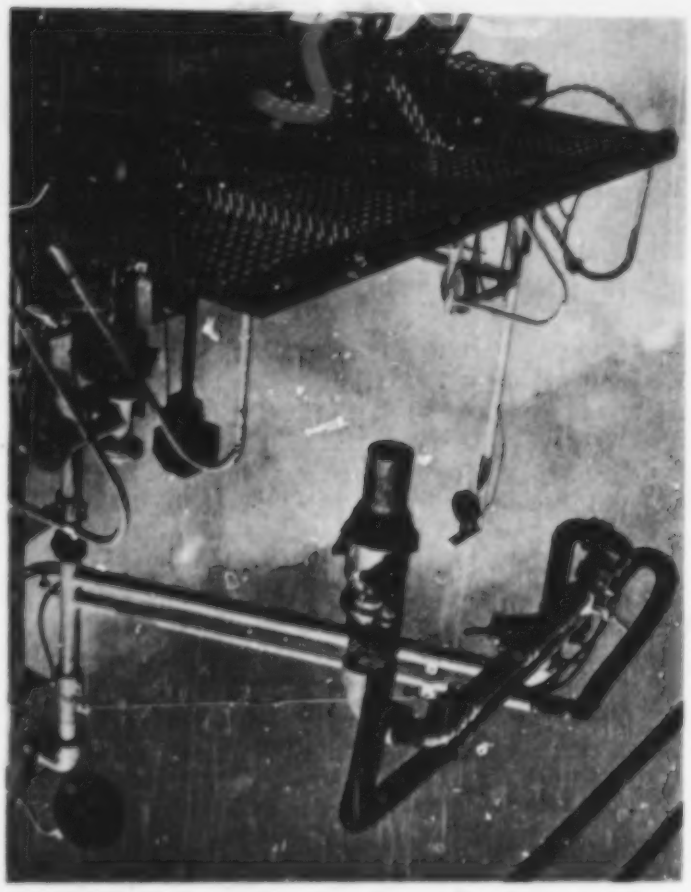


Figure 462. A closeup view of a controlled loading arm with the access platform in a lowered position (Phillips Petroleum, Los Angeles, Calif.).

than submerged filling does, other conditions being equal. On the basis of a typical 50 percent splash filling operation, vapor losses from the overhead filling of tank vehicles with gasoline have been determined empirically to amount to 0.1 to 0.3 percent of the volume loaded (Deckert et al., 1958). Figure 466 presents a correlation of loading losses with gasoline vapor pressures.

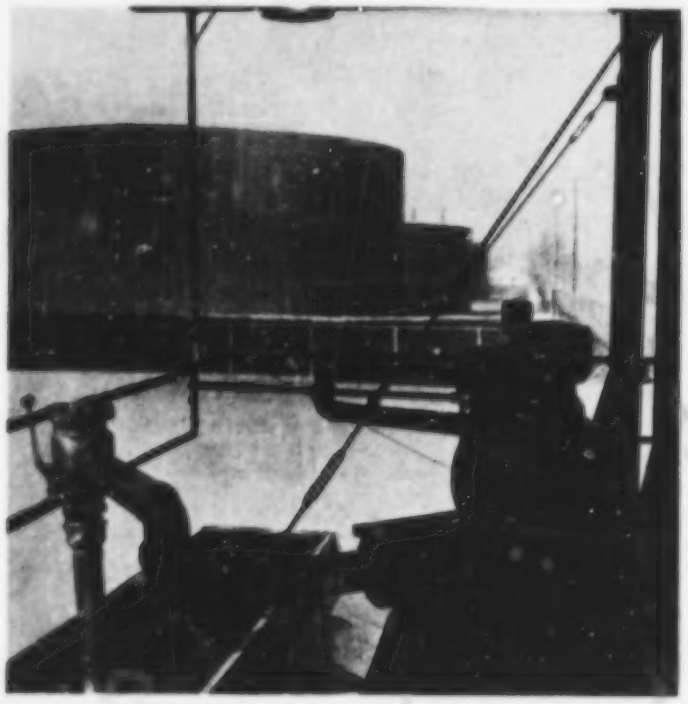


Figure 464. View of uncontrolled loading arm.

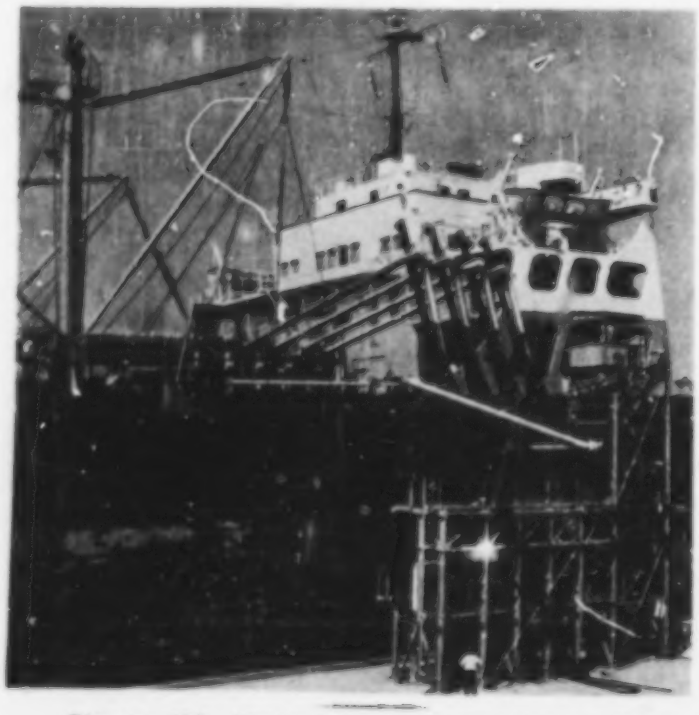


Figure 463. Marine terminal loading station (Chiksan Company, Brea, Calif.).

Figure 465. View of a pneumatically operated loading arm (Union Oil Company of California, Los Angeles, Calif.).

Table 173. TYPICAL ANALYSIS OF VAPORS FROM THE BULK LOADING OF GASOLINE INTO TANK TRUCKS
(Deckert et al., 1958)

Fraction	Vol %		Wt %	
Air		58.1		37.6
Hydrocarbon				
Propane	0.6		0.6	
Iso-Butane	2.9		3.8	
Butene	3.2		4.0	
N-Butane	17.4	41.9	22.5	62.4
Iso-Pentane	7.7		12.4	
Pentene	5.1		8.0	
N-Pentane	2.0		3.1	
Hexane	3.0		8.0	
		100.0		100.0

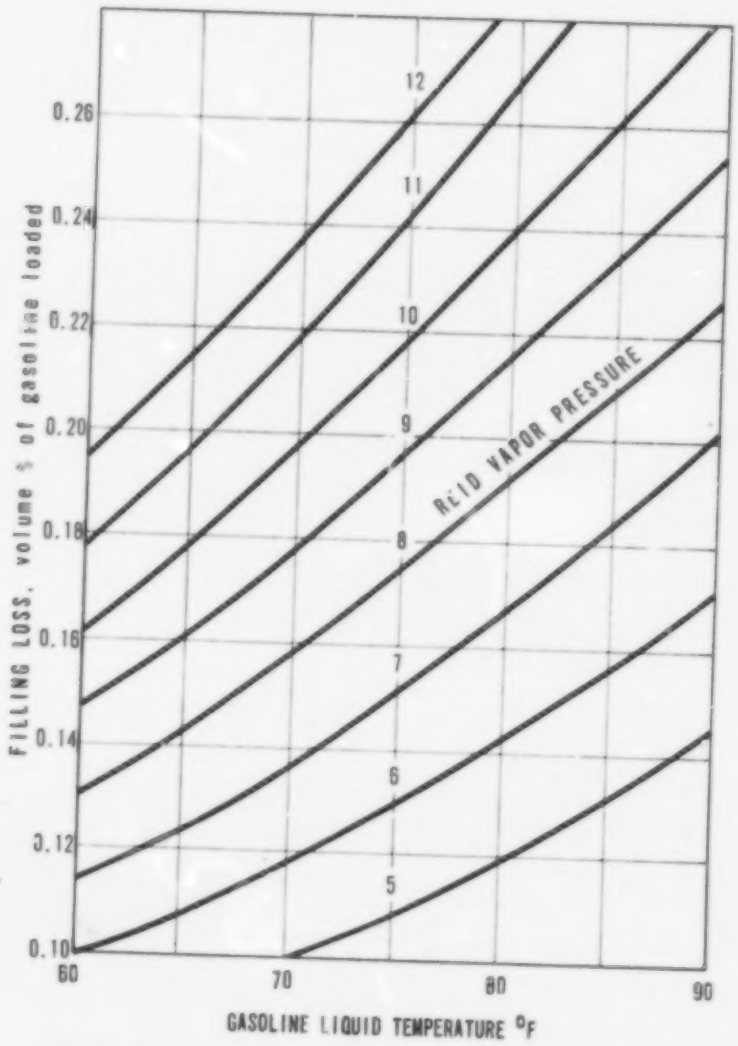


Figure 466. Correlation of tank vehicle-loading losses (50% submerged filling) with Reid vapor pressure and liquid temperatures of the motor gasoline.

Bottom loading has been introduced by a few oil companies and found practical for loading trucks (Hunter, 1959). The equipment required is simpler than that used for overhead loading. Loading by this method is accomplished by connecting a swing-type loading arm or hose at ground level, as shown in Figure 467, to a matching fitting on the underside of the tank vehicles. Aircraft-type, quick-coupling valves are used to ensure a fast, positive shutoff and prevent liquid spills. Several companies experienced in aircraft-fueling operations have developed fully automatic bottom-loading systems. All the loading is submerged and under a slight pressure; thus, turbulence and resultant production of vapors are minimized.

The method employed for loading marine tankers is essentially a bottom-loading operation. Liquid is delivered to the various compartments through lines that discharge at the bottom of each compartment. The vapors displaced during loading are vented through a manifold line to the top of the ship's mast for discharge to the atmosphere.

In addition to the emissions resulting from the displacement of hydrocarbon vapors from the tank vehicles, additional emissions during loading result from evaporation of spillage, drainage, and leakage of product.

AIR POLLUTION CONTROL EQUIPMENT

An effective system for control of vapor emissions from loading must include a device to collect the vapors at the tank vehicle hatch and a means for disposal of these vapors.

Types of Vapor Collection Devices for Overhead Loading

Four types of vapor collectors or closures, fitting the loading tube, have been developed for use during overhead-loading operations of trucks: The General Petroleum Corporation unit, the Vernon Tool Company or Greenwood unit, the SOCO unit, and the Chiksan unit. All are essentially plug-shaped devices that fit into the hatch openings and have a central channel through which gasoline can flow into the tank vehicle compartment. This central channel, actually a section of the loading tube, is surrounded by an annular vapor space. Entry into this vapor space is achieved through openings on the bottom of the closure that are below the point of contact of the external closure surface with the sides of the hatch opening. Thus, vapors are prevented from passing around the closure and out of the hatch, and must flow in-

Figure 467. View of a bottom-loading station (Standard Oil Company of California, Western Operations Inc., Los Angeles, Calif.).

stead into the annular space, which in turn, is connected to a hose or pipe leading to a vapor disposal system.

The vapor closure device developed by the General Petroleum Corporation (now Mobil Oil Corp.) has the annular vapor space connected to an auxiliary, transparent, plexiglas vapor chamber section above the closure to allow the operator to observe the calibrated capacity markers.* A typical Mobil Oil Corporation vapor closure is shown in Figure 468. A neoprene rubber bellows above the plexiglas chamber compensates for vertical misalignment of the closure in the hatch opening. The closure is aluminum and is cast in the shape of a truncated cone. The lateral surface of the closure is faced with a neoprene rubber gasket in the shape of a spherical section so as to give a vaportight seal between the closure and the hatch when the closure is positioned in the hatch for loading. The top of the closure has openings for the loading tube and the vapor takeoff line. An adjustable slipring serves as a positioner enabling the loading operators to slide the closure to the proper height on the loading tube for various depths of tank vehicle compartments. This closure requires a constant downward force to keep it in contact with the hatch opening's sides at all times during filling and is built to fit only hatches 8 to 10 inches in diameter.

*These markers are gages located within the tank compartment and positioned at a calibrated volume to indicate visually the amount of liquid loaded.

The second type of closure, the Greenwood Unit, (Figures 469 and 470), which also requires a downward force during the filling operation, was developed by the Vernon Tool Company. This closure is also cast aluminum in the shape of a plug similar to the Mobil Oil Corporation closure and with a neoprene rubber gasket. This closure has no auxiliary, transparent, vapor chamber section, though some versions of this closure do have auxiliary, metal vapor chambers or a transparent, light well. The closure fits tank truck compartments with hatches from 8 to 10 inches in diameter. Since compartments with hatches of larger diameters are sometimes encountered, an adapter has been provided. The adapter consists of a flat, gasketed plate with an 8-inch-diameter hole in the center through which the closure can be inserted.

The third type of vapor closure, referred to as SOCO, was developed by Standard Oil Company of California (Figures 471, 472, and 473). It consists of an aluminum cast plug of more complicated design. This closure is locked into the hatch opening by a cam lever that forces a floating, internal, cylindrical section to move upward and squeeze a neoprene rubber collar out against the sides of the hatch opening, which effects a vaportight seal during all phases of loading. As the floating, internal, cylindrical section is rolled upward by the action of the cam lever device, it exposes the vapor entry opening. A piston-type, internal filling valve, similar to an aircraft-fueling valve, was developed for this closure. A safety shutoff float operates a needle

Figure 468. View of General Petroleum Corporation Vapor closure (Mobil Oil Corporation, Los Angeles, Calif.).

pilot valve that controls the internal valve to prevent overfilling. The cam lever must be released to remove the vapor closure. The floating cylinder is returned to the closed position at the same time. Thus, the vapor side is sealed off to prevent any leakage from the vapor-gathering lines. At the same time the internal valve is locked in the closed position. SOCO closures fit only hatches 8 inches in diameter, though adapters have been developed for hatches of greater diameter. This adapter is a circular casting with an 8-inch opening and is placed over the hatch opening. When the SOCO unit is inserted, spring-loaded arms act to clamp and seal the adapter against the top of the hatch.

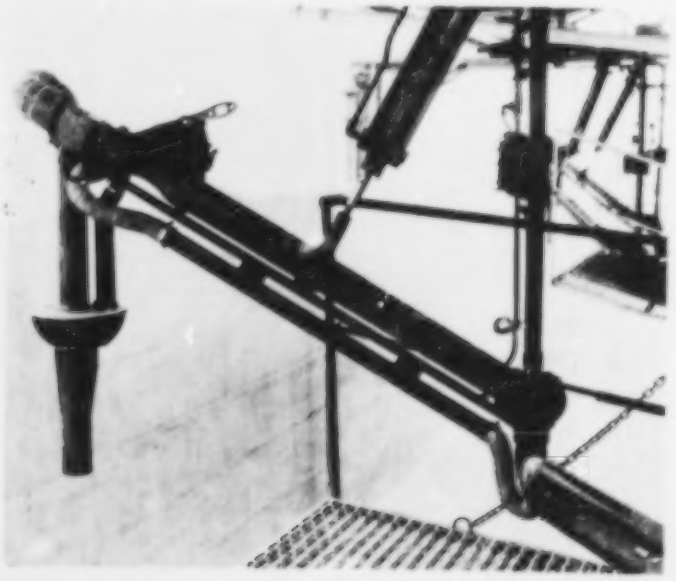


Figure 469. View of the Greenwood vapor closure (Atlantic-Richfield Oil Corporation, Los Angeles, Calif.).

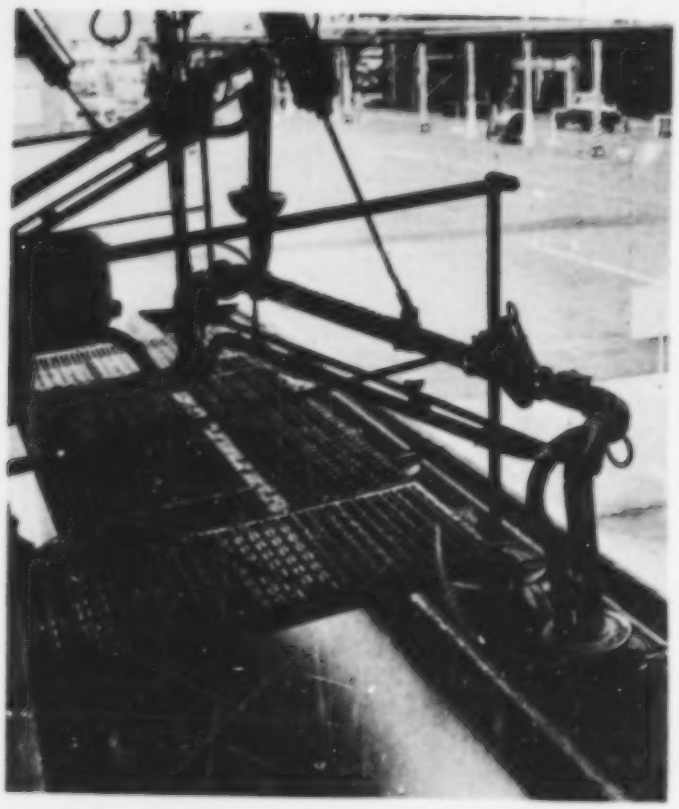


Figure 470. Closeup view of Greenwood vapor closure (Atlantic-Richield Oil Corporation, Los Angeles, Calif.).

The Chiksan Company has recently offered a fourth system, a modern loading arm that incorporates the hatch closure, the vapor return line, and the fill line as an assembled unit (Figure 474). This unit incorporates features to prevent overfills, topping off, or filling unless

Figure 471. Closeup view of SOCO vapor closure, withdrawn position (American Airlines, Los Angeles, Calif.).

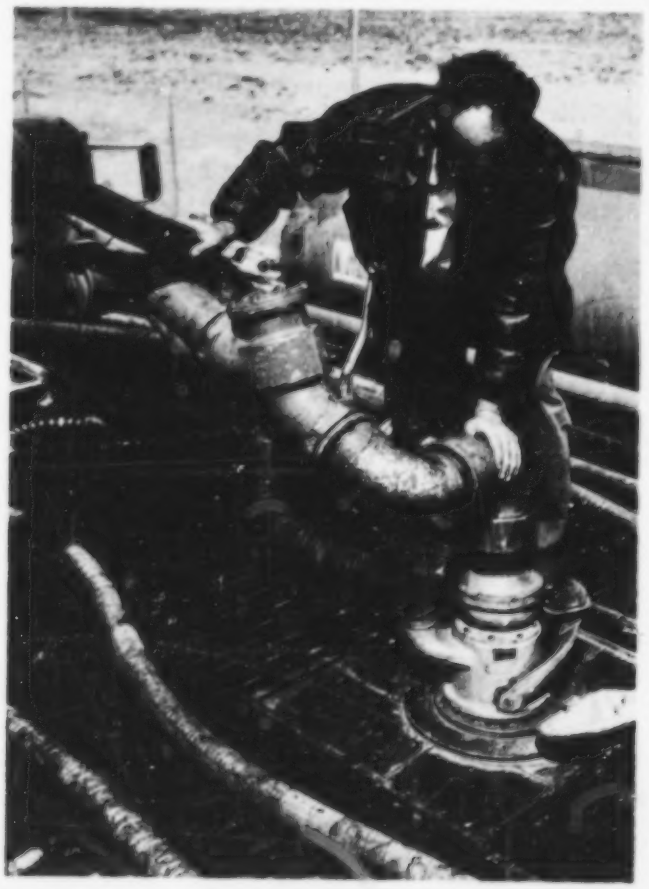


Figure 472. Closeup view of SOCO vapor closure, filling position (American Airlines, Los Angeles, Calif.).

the assembly is properly seated in the truck hatch. A pneumatic system ensures contact with the tank truck as the gasoline is added and provides a delay at the end of the loading cycle to achieve adequate drainage of the arm before it is withdrawn from the truck hatch.

The slide positioner of the Mobil Oil Corporation vapor closure, though permitting adjustments for submerged loading, can be a source of vapor leaks and requires proper attention by the operator. SOCO closures with inner valves are considerably heavier than other types, and the inner valve involves added pressure drops, which slow the loading rates. Both the Greenwood and the Mobil Oil Corporation closures require vapor check valves in the vapor-gathering lines to prevent the vapor from discharging back to the atmosphere when the loading assembly is withdrawn. In addition, inspections have shown that the Mobil Oil Corporation and Greenwood closures require nearly vertical entry of the loading tube into the compartment hatch opening in order to provide a tight seal against vapor leaks. A connecting rod between the riser and filling stem has been added to some assemblies, as shown in Figure 475, to form a pantograph arrangement to maintain the filling stem of the loading arm in the vertical position at all times. The loading operator is thus able to obtain good sealing contact more quickly between the vapor collector and the hatch opening.

Collection of Vapors From Bottom Loading

Vapors displaced from tank vehicles during the bottom-loading operation are more easily collected than those are that result from overhead loading. The filling line and the vapor collection line are independent of each other with resultant simplification of the design (see Figure 476). The vapor collection line is usually similar to the loading line, consisting of a flexible hose or swing-type arm connected to a quick-acting valve fitting on the dome of the vehicle. This fitting could be placed at ground level to simplify the operation further.

A check valve must be installed on the vapor collection line to prevent backflow of vapors to the atmosphere when the connection to the tank vehicle is broken.

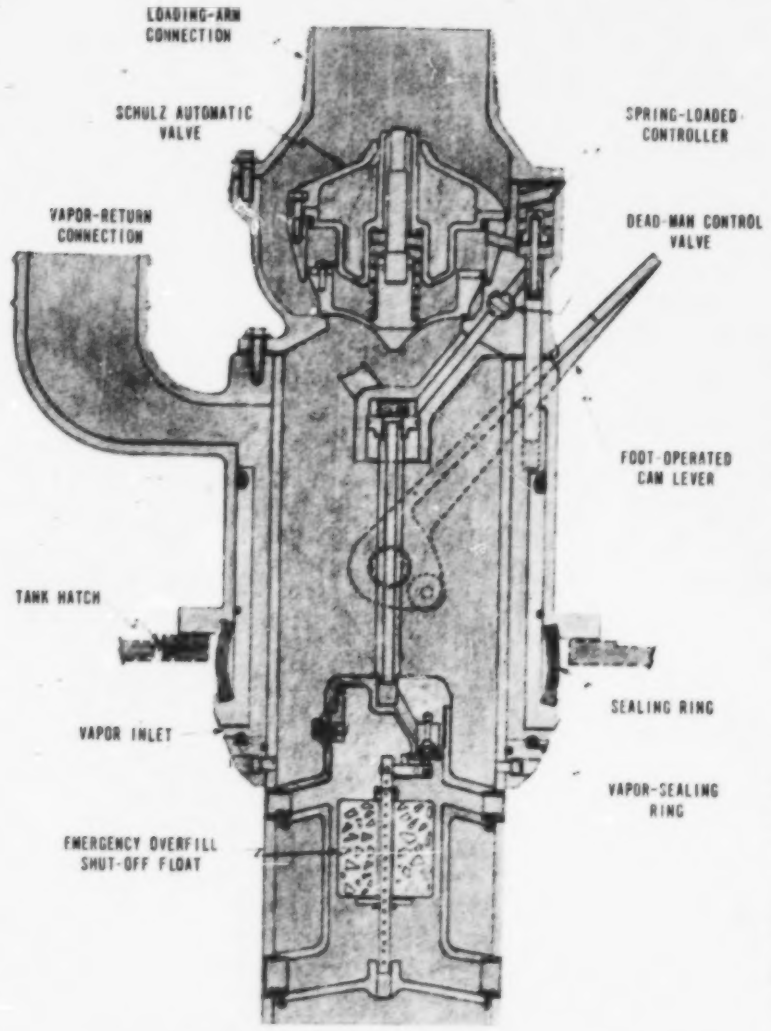


Figure 473. Schematic drawing of SOCO vapor closure used to collect displaced vapors during loading (Standard Oil Company of California, Western Operations, Inc., Los Angeles, Calif.).

Factors Affecting Design of Vapor Collection Apparatus

In designing for complete vapor pickup at the tank vehicle hatch, several factors, including tank settling, liquid drainage, and topping off must be considered.

The settling of a tank vehicle due to the weight of product being added requires that provision be made for vertical travel of the loading arm to follow the motion of the vehicle so that the vapor collector remains sealed in the tank hatch during the entire loading cycle. Two solutions to the problem of settling have been used. The first, applicable to pneumatically operated arms, includes the continuous application of air pressure to the piston in the air cylinder acting on the arm. The arm is thus forced to follow the motion of the vehicle without need for clamping or fastening the vapor collector to the tank vehicle. The second solution, employed on counterweighted and torsion spring loading arms, provides for locking the vapor collector to the tank vehicle hatch. The arm then necessarily follows the motion of the vehicle. The second solution is also applicable to vapor collection arms or hoses that are connected to the top of a tank vehicle during bottom loading.

The second problem, that of preventing considerable liquid drainage from a loading arm as it is withdrawn after completion of filling operations, has been adequately solved. The air valve that operates the air cylinder of pneumatically operated loading arms may be modified by addition of an orifice on the discharge side of the valve. The orifice allows 30 to 45 seconds to elapse before the loading assembly clears the hatch compartment. This time interval is suffi-

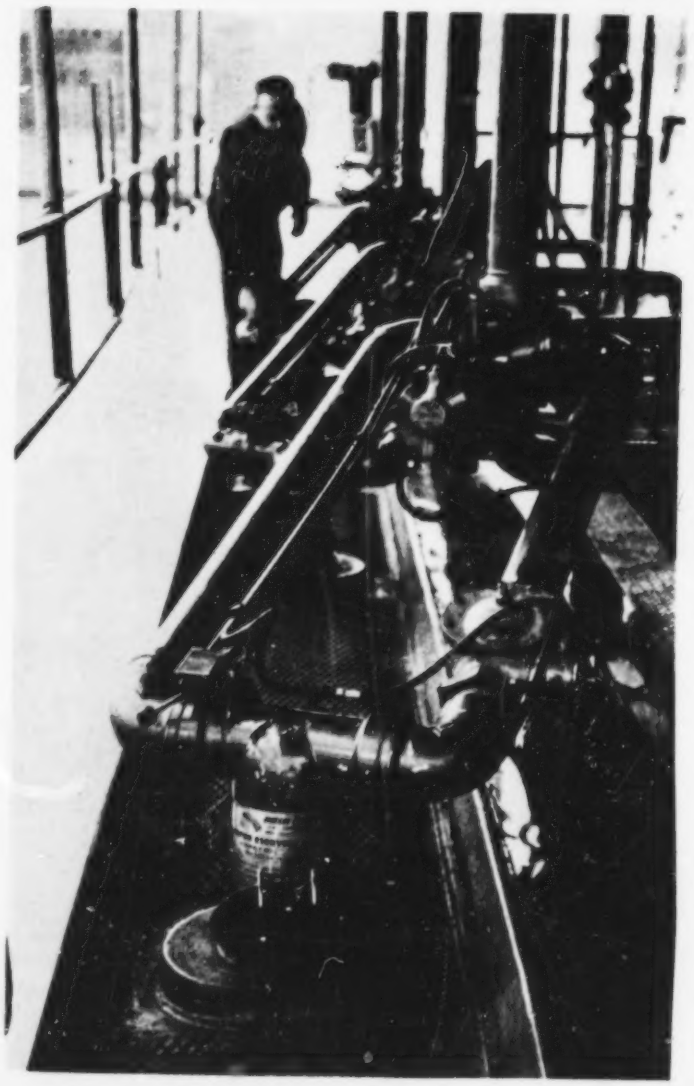


Figure 474. View of a pneumatically operated loading assembly with an integrated vapor closure and return line (Chiksan Co., Brea, Calif.).

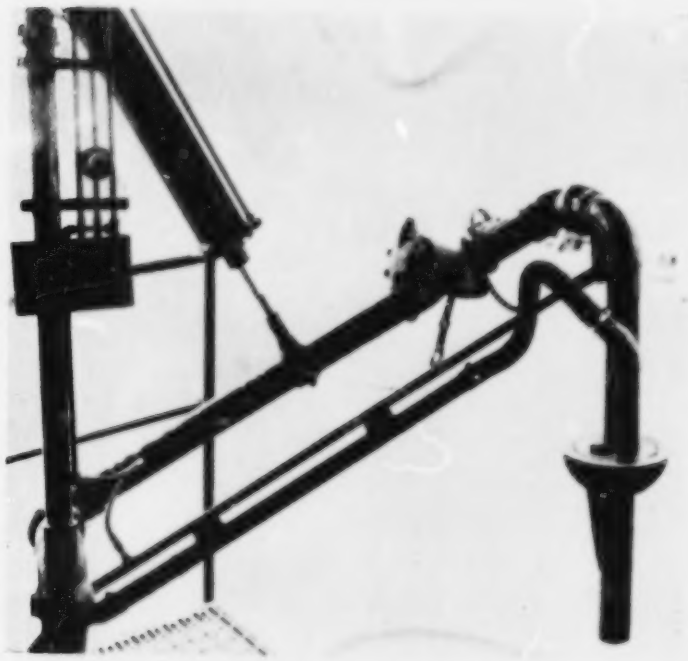


Figure 475. View of a pneumatically operated loading arm showing pantograph linkage (Atlantic-Richfield Oil Corporation, Los Angeles, Calif.).

Figure 476. Bottom loading of tank trucks provides one way to collect vapor during loading in conjunction with the use of return line to storage tanks (Standard Oil Company of California, Western Operations, Inc., Los Angeles, Calif.).

cient to permit complete draining of liquid into tank compartments from arms fitted with loading valves located in an outboard position. Loading arms with inboard valves require additional drainage time and present the problem of gasoline retention in the horizontal section of the arm. To prevent drainage the SOCO vapor collection closure is fitted with an internal shutoff valve that is closed before the loading arm is withdrawn from the tank hatch. Providing for thermal expansion has been found necessary when an inboard valve and a SOCO vapor closure are used. This has been accomplished by installing a small expansion chamber at the normal position of the loading arm's vacuum breaker. In bottom loading, the valve coupling at the end of the loading arm or hose, as well as the mating portion of the valve on the trucks, is self-sealing to prevent drainage of product when the connection is made or broken.

The third factor to be considered in the design of an effective vapor collection system is topping off. Topping off is the term applied to the loading operation during which the liquid level is adjusted to the capacity marker inside the tank vehicle compartment. Since the loading arm is out of the compartment hatch during the topping operation, vapor pickup by the collector is nil. Metering the desired volumes during loading is one solution to the problem. Metered loading must, however, be restricted to empty trucks or to trucks prechecked for loading volume available. Accuracy of certain totalizing meters or preset stop meters is satisfactory for loading without the need for subsequent open topping. An interlock device for the pneumatic-type loading arms, consisting of pneumatic control or mechanical linkage, prevents opening of the loading valve unless the air cylinder valve is in the down position. Thus, open topping is theoretically impossible.

Topping off is not a problem when bottom loading is employed. Metered loading, or installation of a sensing device in the vehicle compartments that actuates a shutoff valve located either on the truck or the loading island, eliminates the need for topping off.

Methods of Vapor Disposal

The methods of disposing of vapors collected during loading operations may be considered under three headings: Using the vapors as fuel, processing the vapors for recovery of hydrocarbons, or effecting a vapor balance system in conjunction with submerged loading.

The first method of disposal, using the vapors directly as fuel, may be employed when the loading facilities are located in or near a facility that includes fired heaters or boilers. In a typical disposal system, the displaced vapors flow through a drip pot to a small vapor holder that is gas blanketed to prevent forming of explosive mixtures. The vapors are drawn from the holder by a compressor and are discharged to the fuel gas system.

The second method of disposal uses equipment designed to recover the hydrocarbon vapors. Vapors have been successfully absorbed in a liquid such as gasoline or kerosine. If the loading facility is located near a refinery or gas absorption plant, the vapor line can be connected from the loading facility to an existing vapor recovery system through a regulator valve.

Vapors are recovered from loading installations distant from existing processing facilities by use of package units. One such unit (Figures 477 and 478) that absorbs hydrocarbon vapors in gasoline has been developed by the Superior Tank and Construction Company. This unit includes a vaporsphere or tank equipped with flexible membrane diaphragm, saturator, absorber, compressor, pumps, and instrumentation. Units are available to fit any size operation at any desired loading location since they use the gasoline product as the absorbent.

Explosive mixtures must be prevented from existing in this unit. This is accomplished by passing the vapors displaced at the loading rack through a saturator countercurrently to gasoline pumped from storage. The saturated vapors then flow to the vaporsphere. Position of the diaphragm in the vaporsphere automatically actuates a compressor that draws the vapors from the sphere and injects them at about 200 psig into the absorber. Countercurrent flow of stripped gasoline from the saturator or of fresh gasoline from storage is used to absorb the hydrocarbon vapors. Gasoline from the absorber bottoms is returned to storage while the tail gases, essentially air, are released to the atmosphere through a backpressure regulator. Some difficulty has been experienced with air entrained or dissolved in the sponge gasoline returning to storage. Any air released in the storage tank is discharged to the atmosphere saturated with hydrocarbon vapors. A considerable portion of the air can be removed by flashing the liquid gasoline from the absorber in one or more additional vessels operating at successively lower pressures.

Another type of package unit adsorbs the hydrocarbon vapors on activated carbon, but no installation of this kind has been observed in Los Angeles County. The application of this type of unit is presently restricted to loading installations

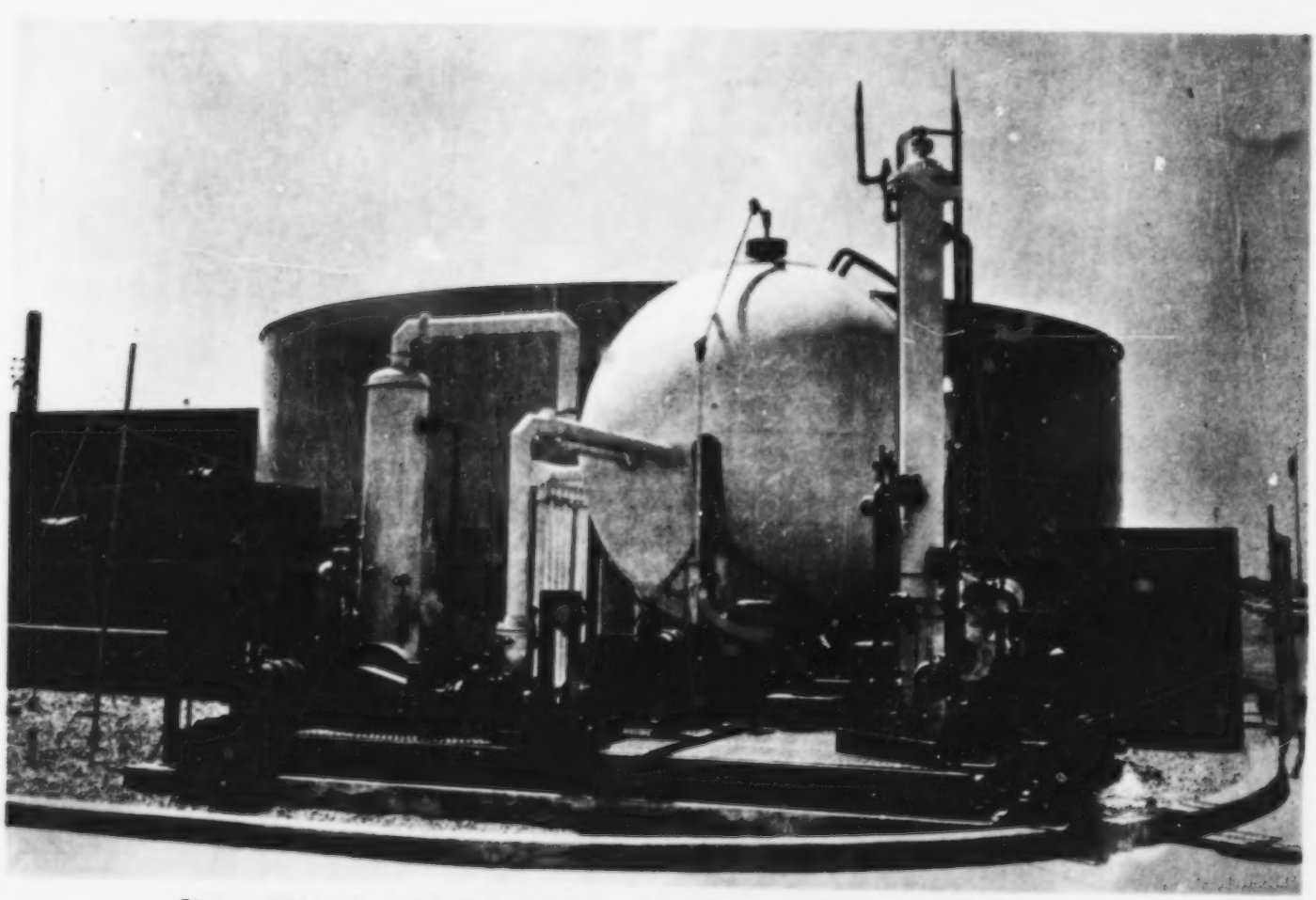


Figure 477. View of small-capacity vaporsaver gasoline absorption unit (American Airlines, Los Angeles, Calif.).

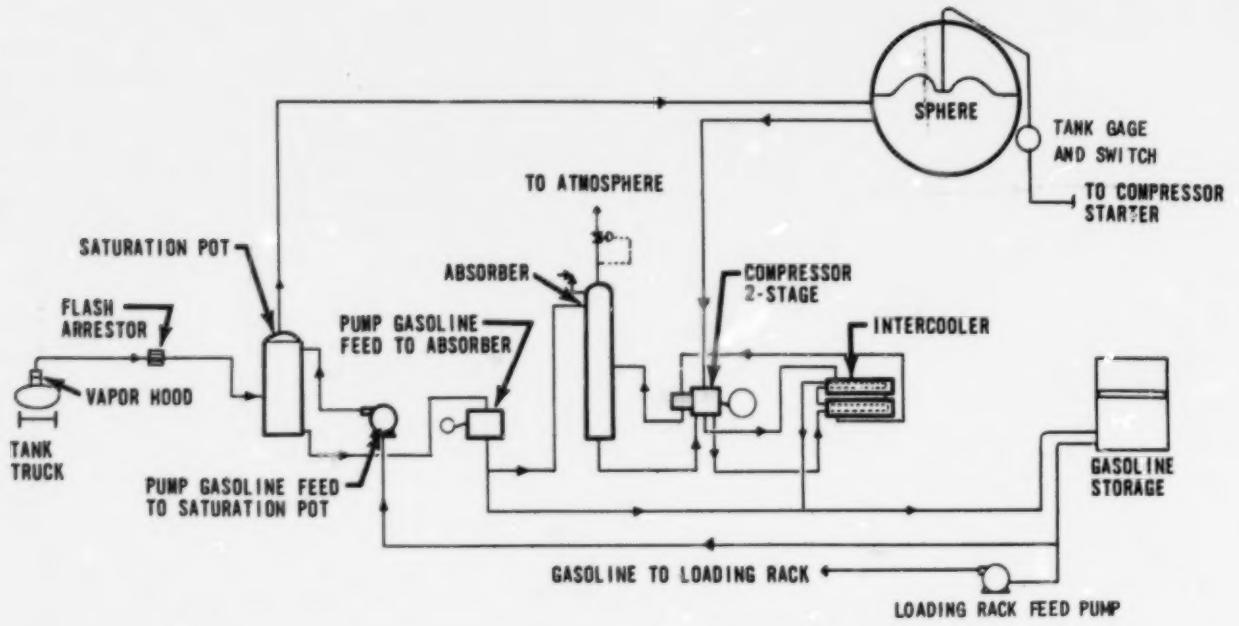


Figure 478. Schematic flow diagram of a vaporsaver unit used for recovery of loading rack vapors at a bulk terminal.

that have low throughputs of gasoline, since the adsorbing capacity and the life of the carbon are limited. Units of this type find application in control of vapors resulting from fueling of jet aircraft.

The vapors displaced during bottom filling are minimal. Data indicate a volume displacement ratio of vapor to liquid of nearly 1:1. A closed system can then be employed by returning all the displaced vapors to a storage tank. The storage tank should be connected to a vapor recovery system.

CATALYST REGENERATION

Modern petroleum processes of cracking, reforming, hydrotreating, alkylation, polymerization, isomerization, and hydrocracking are commercially feasible because of materials called catalysts. Catalysts have the ability, when in contact with a reactant or mixture of reactants, to accelerate preferentially or retard the rate of specific reactions and to do this, with few exceptions, without being chemically altered themselves. Different catalysts vary in their effects. One might, for example, increase oxidation rates while another might change the rate of dehydrogenation or alkylation.

Contact between the catalyst and reactants is achieved in some processes by passing the reac tants through fixed beds or layers of catalysts contained in a reactor vessel. Contact in other processes involves simultaneous charging of catalyst and reactants to a reactor vessel and withdrawal of used catalyst in one stream, and products and unreacted materials in another stream. The first process may be termed a fixed-bed system and the latter a moving-bed system. Moving-bed systems may be further subclassified by the type of catalyst and method of transporting it through the process. Examples are the use of vaporized charge material to fluidize powdered catalyst, as in fluid catalytic cracking units (FCC), and the use of bucket elevators, screws, airlifts, and so forth, to move the catalyst pellets or beads, as in Thermofor catalytic cracking units (TCC) (see Figures 479, 480, and 481).

TYPES OF CATALYSTS

Generally, the catalysts are used in the form of solids at process temperatures, though some liquid catalysts are used alone or impregnated into inert solid carriers. Pellets, beads, and powders are the common physical shapes. Cracking catalysts are usually beads or powders of synthetic silica-alumina compositions, including acid-treated bentonite clay, Fuller's earth, aluminum hydrosilicates, and bauxite. Little-used synthetic catalysts include silica-magnesia, alumina-boria, and silica-zirconia (Nelson, 1958). Bead or pelleted catalyst, noted for ease of handling and freedom from plugging, is used in TCC units while powdered catalyst is used in FCC units. Natural catalysts are softer and fail more rapidly at high temperatures than most synthetic

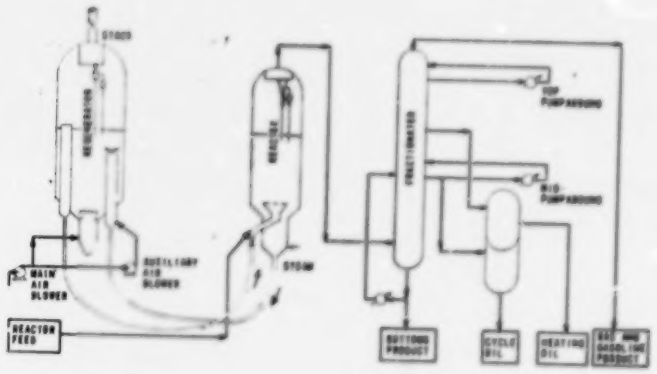


Figure 479. Simplified flow diagram of a Model IV fluid catalytic cracking unit (Oil and Gas Journal, 1957).

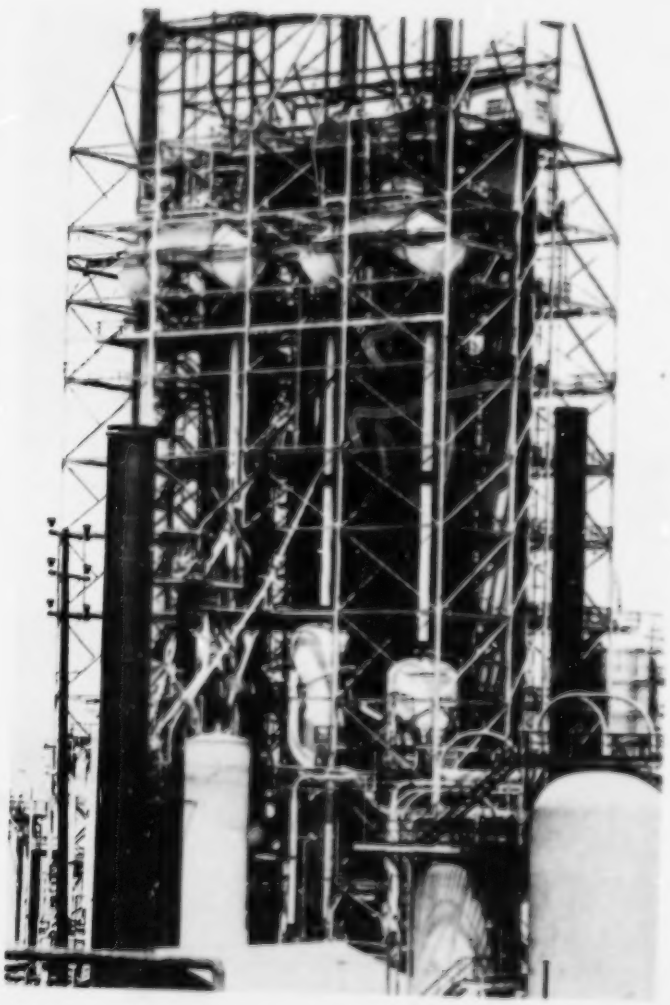


Figure 480. Thermofor catalytic cracking unit (Union Oil Company of California, Los Angeles, Calif.).

catalysts do. The cost of natural catalysts, however, is under $100 per ton while synthetic types cost $300 or more per ton.

Catalysts employed in catalytic reforming include the platinum-containing catalysts used in modern fixed-bed reformers, except for the bauxite pellet catalyst for Cycloversion used at 950° to 1,000°F and 50 to 57 psig, and the molybdena-alumina catalysts used for fluid hydroforming. Fixed-bed reactors operate at 825° to 1,000°F and 200 to 1,000 psig with catalyst pellets about 1/8 inch in diameter. These catalysts contain less than 1 percent platinum and are supported on a base of either alumina or silica-alumina. Acid-type catalyst required for reforming processes may be provided by one of the oxides as the catalyst base. The acid may be a halogen compound add-

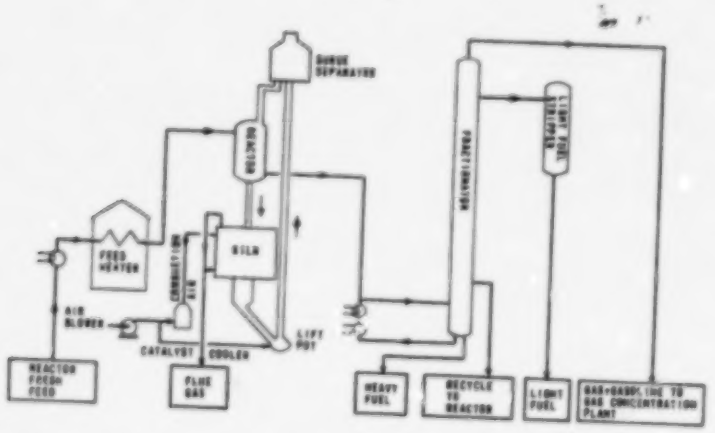


Figure 481. Simplified flow diagram of Thermofor catalytic cracking unit with modern catalyst air-lift (Oil and Gas Journal, 1957).

ed to the catalyst, or may be directly added to the reformer charge. The flow diagram of a platforming process is shown in Figure 482.

The major desulfurization processes-Autofining, Dieselforming, HDS, Hydrofining, Ultrafining, Unifining, and so forth--employ a cobalt-molybdenum catalyst supported on bauxite and operate within a range of 450° to 850°F and 50 to 1,500 psig.

Commercial alkylation processes employ as catalysts either sulfuric acid, hydrogen fluoride, or aluminum chloride with a hydrogen chloride promoter.

Commercial polymerization catalysts consist of a thin film of phosphoric acid on fine-mesh quartz, copper pyrophosphate, or a calcined mixture of phosphoric acid.

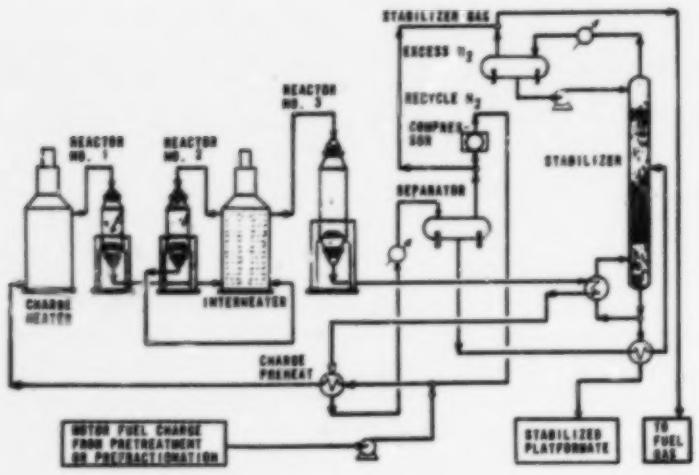


Figure 482. Simplified flow diagram of platforming process (Oil and Gas Journal, 1957).

Isomerization processes such as Butamer, Isokel, Isomerate, Penex, and Pentafining employ a noble metal, usually platinum, as the catalyst in a hydrogen atmosphere. Liquid-phase isomerization is accomplished with aluminum chloride in molten antimony chloride with a hydrogen chloride activator.

Loss of Catalyst Activity

The activity of a catalyst, or its effectiveness in changing rates of specific reactions decreases with on-stream time. The rate of decrease is related to composition of reactants contacted, throughput rate, and operating conditions. Loss of activity results from metal contamination and poisoning or deposits that coat the catalyst surfaces and thus reduce the catalytic area available for contact with the reactants. Frequently carbon from the coking of organic materials is the main deposit. To continue in successful operation, catalyst activity must be restored. One procedure consists of replacing the spent catalyst with fresh catalyst. A second procedure consists of treating the spent catalyst for removal of contaminants. This latter procedure, called catalyst regeneration, is the more significant from the standpoint of air pollution, since combustion is frequently the method of regeneration.

In fixed-bed systems, catalysts are regenerated periodically in the reactor or removed and returned to the manufacturer for regeneration. In moving-bed systems, catalysts are continuously removed from the reactor, regenerated in a special regenerator vessel, and returned to the reactor.

REGENERATION PROCESSES

Catalysts for the catalytic cracking and reforming processes are regenerated to restore activity by burning off the carbon (coke) and other deposits from the catalyst surface at controlled temperature and regeneration air rates. Actually, the so-called "carbon" on the catalyst is not all pure carbon but contains other compounds. Moreover, the catalyst is not entirely freed of the carbon deposits during regeneration, though an effort is made to keep the residual carbon below 0.9 percent by weight on the regenerated catalyst. FCC units, all of which have continuous catalyst regeneration, have a coke burnoff rate 5 to 10 times higher than TCC unit regenerators have. Since fixed-bed reformer units, which incorporate catalyst regeneration, have a very small coke laydown on the catalyst surface, they require regeneration only once or twice a year, as the desulfurizer reactors do, which have both a coke and sulfur laydown.

FCC Catalyst Regenerators

Catalyst regenerators for FCC units may be located alongside, above, or below the reactor. Regenerators normally have a vertical, cylindrical shape with a domed top. The inside shell of the regenerator is insulated with 4 to 6 inches of refractory lining. This lining may also be extended into the regenerator's discharge line and the regenerator's catalyst charge line.

The upper section of the regenerator is equipped with internal cyclone separators to separate the catalyst dust from the regeneration combustion gases. The number of cyclone separators varies from a single-stage or two-stage separator to as many as 12 sets of three-stage cyclone separators. External size of the regenerator varies from 20 feet in diameter by 40 feet high to 50 feet in diameter by 85 feet high. In Los Angeles County, regenerator flue gases pass through additional equipment, consisting of electrical precipitators or cyclone separators and electrical precipitators for final dust removal, before discharging to the atmosphere. Carbon monoxide waste-heat boilers are employed before or following the electrical precipitators.

In a typical FCC unit, as shown in Figure 479, the spent catalyst from the base of the reactor is steam stripped to remove residual hydrocarbons and then transferred to the regenerator by injecting preheated air into the transfer line. Burning off of the carbon starts when the hot, spent catalyst contacts the air, and continues as the catalyst flows up through the regenerator to the overflow well. Additional combustion air is furnished by the main blower. The amount of air supplied is controlled to prevent glazing the catalyst. This results in the formation of considerable amounts of carbon monoxide. The depth of the fluidized catalyst bed is usually limited to

15 feet to prevent the load on the cyclones from being excessive. Regenerated catalyst flows down through the overflow well to the reactor as a result of a slight pressure differential.

The flue gases pass through the regenerator's cyclone separators, for removal of most of the catalyst more than 10 microns in size; through a steam generator, where process steam is made; through a pressure-reducing chamber to air pollution control units; and then to the atmosphere. The pressure-reducing chamber serves as a noise suppressor. Final dust cleanup is accomplished by passing the effluent gases from the cyclone separators through an electric precipitator. The gases from the precipitator are introduced into a carbon monoxide boiler where the sensible heat and the heat content of the CO is used to produce steam in some flow schemes. Other operations place the waste-heat boiler before the precipitator.

According to Brown and Wainwright (1952), the weight of dust per cubic foot of exit gas remains constant at about 0.002 pound at bed velocities up to a critical velocity of 1.5 fps, whereupon it rises rapidly with higher velocities, for example, to 0.01 pound at 1.8 fps. The pressures in FCC unit regenerators are always low, between 1 and 10 psig. Regeneration temperatures are usually between 1,050° and 1,150°F. Other general operating data for large and small FCC unit regenerators are as follows:

	Small unit	Large unit
Catalyst circulation rate, tons/min	10	60
Coke burnoff rate, lb/hr	5,000	34,000
Regeneration air rate, scfm	13,000	102,000

TCC Catalyst Regenerators

TCC (and Houdry unit) catalyst regenerators, referred to as kilns, are usually vertical structures with horizontal, rectangular, or square cross sections. A regenerator that has a catalyst circulation rate of 150 tons per hour would have an outside dimension of about 11 feet square by 43 feet high. This size regenerator, or kiln, has approximately 10 regeneration zones and a topside kiln hopper. Each zone is equipped with a flue gas duct, air distributors, and steam- or water-cooling coils. The carbon steel shell of the regenerator is lined with about 4 inches of firebrick, which is, in turn, covered with alloy steel. The discharge flue gases from the regeneration kilns are usually vented through dry-type, centrifugal dust collectors.

In a TCC unit, Figure 480, spent catalyst (beads) from the base of the reactor is steam purged for removal of hydrocarbons and lifted by a bucket elevator to a hopper above the regeneration kiln. Catalyst fines at this point in the process are separated from catalyst beads in an elutriator vessel using up-flowing gases and are collected from these gases in a cyclone separator discharging to a fines bin. Spent catalyst beads drop through a series of combustion zones, each of which contains flue gas collectors, combustion air distributors, and cooling coils. The catalyst is regenerated as it flows downward through the kiln zones countercurrent to preheated air (400° to 900°F). The pressure is essentially atmospheric in the kiln. Water is circulated through cooling coils in each kiln zone to control the rate of coke combustion. The regeneration temperatures at the top of the kiln are between 800° and 900°F, while the bottom section of the kiln operates between 1,000° and 1,100°F. A minimum temperature of 900°F is required for catalyst regeneration. An average-size TCC unit regenerator with a catalyst circulation of 2.5 tons per minute has a coke burnoff rate of 3,500 pounds per hour and a regeneration air rate of 24,000 scfm.

Regenerated catalyst from the bottom of the kiln is then transferred by bucket elevator to the catalyst bin for reuse in the reactor. The more modern TCC units use a catalyst airlift (Figure 481) rather than bucket elevators for returning regenerated catalyst to the reactor, and gravity flow for moving spent catalyst to the regenerator. The elevators of those units must be vented through wet centrifugal collectors or scrubbers to the atmosphere.

Catalyst Regeneration in Catalytic Reformer Units

Some types of catalytic reformer units are shut down once or twice each year for regeneration of the catalyst in the desulfurizer reactor. Reforming units using Sinclair-Baker catalyst are in this category. Before the regenerating, the reformer system is depressured, first to the fuel gas system and then to vapor recovery. A steam jet discharging to vapor recovery is then used to evacuate the reformer further to 100 millimeters of mercury absolute pressure. An inert gas such as nitrogen is introduced to purge and then repressure the system to 50 psig. The nitrogen is circulated by the recycle gas compressor through the heaters, reactors, heat exchangers, flash drum, and regeneration gas drier. Inert gas circulation is continued while combustion air for burning off the coke is introduced into the top of the first reactor by the regeneration air compressor. The rate of air is controlled to maintain catalyst bed temperatures below 850°F. Pressure is controlled to 150 psig by releasing products of combustion to the fire-

box of the reformer heater. After burning is completed in the first reactor, as indicated by the rise in oxygen content in the effluent, the air supply is then switched to the second reactor. The same procedure is repeated for the other reactors.

In the regeneration cycle, circulation of approximately 15,000 scfm flue gas is maintained by using the reformer recycle gas compressor, and approximately 500 scfm regeneration air is added for burning off the coke. About 24 to 30 hours is required for regeneration, based upon a coke content of 5 percent by weight in the catalyst. The coke may run about 90 percent carbon and 10 percent hydrogen.

Desulfurization reactors are depressured in the same manner as the catalytic reformer described. During catalyst regeneration, however, superheated steam is added along with inert air containing about 1.4 mol percent oxygen to effect temperature control. In addition to coke, there are also sulfur deposits that are burned to sulfur dioxide. In some installations the regeneration gases are passed through packed scrubbers that use water or caustic for partial absorption of sulfur dioxide. These reactors are also regenerated for a period of approximately 24 hours about once or twice a year.

Regeneration of fluid hydroforming catalyst, a white powder consisting of molybdena-coated alumina, is accomplished by continuously withdrawing a portion of the catalyst recirculating in the reactor and burning the carbon off in a separate regenerator using fresh air with no preheat. The regeneration temperature is 1,100° to 1,150°F at 200 to 250 psig with 100 percent carbon removal. Molybdenum sulfide, formed by the reaction of catalyst molybdenum oxide and feed stock sulfur, is reoxidized to molybdenum oxide with the release of sulfur dioxide during regeneration.

In alkylation units using hydrogen fluoride as catalyst, the acid strength is restored by removing the water of dilution by distillation. The effectiveness of alkylation units using sulfuric acid as the catalyst is maintained by adding fresh acid as spent acid is withdrawn. The spent acid may be reconcentrated or used as is for other purposes.

Phosphoric acid catalyst used in polymerization units is regenerated by water washing, steaming, and drying the fine-mesh quartz carrier, and adding fresh phosphoric acid. After the excess acid is drained, the reactor is ready to go back on stream.

Many of the remaining catalytic processes require only infrequent catalyst replacement or regeneration (Unicracking and Isomax). In the H-Oil process, however, catalyst is continuously replaced.

THE AIR POLLUTION PROBLEM

Air contaminants are invariably released to the atmosphere from regeneration operations, especially from operations involving combustion. The variety of air contaminants released is broad and may include catalyst dust and other particulate matter, oil mists, hydrocarbons, ammonia, sulfur oxides, chlorides, cyanides, nitrogen oxides, carbon monoxide, and aerosols. The contaminants evolved by any one type of regenerator are a function of the compositions of the catalyst and reactant, and operating conditions.

Tables 174 through 179 show stack emissions for regeneration of both FCC and TCC units. The data in these tables are the results of a testing program (Sussman, 1957) to establish the magnitude of the listed components in the catalyst regeneration gases.

The largest quantities of air pollution from catalyst-regenerating operations are experienced in FCC units. The pollutants include carbon monoxide, hydrocarbons, catalyst fines dust, oxides of nitrogen and sulfur, ammonia, aldehydes, and cyanide. Typical losses from fluid catalytic cracking regenerators, based upon Tables 175 through 178, include:

Pollutant	Loss to atmosphere, lb/hr
Carbon monoxide	24,300
Sulfur dioxide	545
Hydrocarbons	231
NO_x as nitrogen dioxide	80.2
Particulate matter	65.5
Ammonia	57.4
Sulfur trioxide	32.7
Aldehydes as formaldehyde	21.6
Cyanides as hydrogen cyanide	0.27

TCC catalyst regeneration produces air contaminants similar to those from FCC catalyst regeneration. Quantities produced, however, are considerably less, as can be seen from Tables 175 through 178. The bead-type catalyst used in TCC units does not result in the large amount of catalyst fines that are encountered in FCC units.

Air pollution problems are not as severe from catalyst regeneration of reforming and desulfurization reactors as those from FCC and TCC units. These reactors are regenerated only once or twice a year for a period of about 24 hours. The burning-off of the coke and sulfur deposits on the

Table 174. OPERATING CHARACTERISTICS OF FLUID AND THERMOFOR CATALYTIC CRACKING UNITS (Sussman, 1957)

Type[a]	Date tested, 1956	Feed rate		Catalyst circulation rate, tons/hr	Regenerator air rate, scfm	Coke burn-off rate, lb/hr	Avg gas temp, °F
		Fresh, bpd	Recycle, bpd				
FCC	10/4	40,000	10,000	4,500	112,000	38,000	820
FCC	12/4	29,500	2,045	1,560	28,000	23,000	510
FCC	8/30	24,000	0	1,380	22,200	21,300	520
FCC	11/27	32,610	13,680	2,532	97,500	36,416	485
TCC	11/1	9,525	1,500	180	27,000	4,715	840
TCC	11/1	8,525	7,400	150	27,000	2,610	700
FCC	10/9	25,000	9,000	3,240	64,000	21,600	530
TCC	10/18	10,000	0	165	22,000	5,655	660
TCC	10/18	8,000	3,000	150	27,600	4,620	610
TCC	9/19	7,071	5,538	150	24,000	4,410	850
TCC	9/19	6,506	5,602	150	25,000	5,020	740
TCC	9/12	7,099	6,004	150	27,000	3,420	810
TCC	9/12	6,053	6,013	120	23,000	3,000	710
FCC	11/8	6,462	606	390	13,300	5,400	610
TCC	12/19	8,000	3,000	200	16,800	3,760	680

[a]All fluid catalytic cracking units are equipped with electrical precipitators; all Thermofor catalytic cracking units are equipped with cyclone collectors.

Table 175. PARTICULATE LOSS FROM FLUID AND THERMOFOR CATALYTIC CRACKING UNIT STACKS (Sussman, 1957)

Type	Total particulate,[a] lb/hr
FCC	57.50
FCC	61.00
FCC	181.00
FCC	58.70
TCC	1.36
TCC	1.64
FCC	28.30
TCC	13.80
TCC	8.06
TCC	3.44
TCC	2.22
TCC	9.53
TCC	10.01
FCC	6.42
TCC	4.30

[a]The total particulate loss includes weight of insoluble solids in the water, and HCL impinger solution added to the alundum thimble catch.

catalyst surface produces hydrocarbons, sulfur dioxide, and carbon monoxide, in addition to carbon dioxide and water.

AIR POLLUTION CONTROL EQUIPMENT

Dust from FCC catalyst regenerators is collected by centrifugal collectors or centrifugal collectors and electrical precipitators. General design features of these collectors are discussed in Chapter 4. Carbon monoxide waste-heat boilers eliminate carbon monoxide and hydrocarbon emissions in FCC regeneration gases. Dry-type, centrifugal dust collectors are used to collect the catalyst fines from TCC regeneration gas. Dust emissions from TCC unit reactors and regenerator catalyst elevators can be adequately controlled by wet- or dry-type, centrifugal collectors. Presently, no TCC units are equipped with carbon monoxide waste-heat boilers. Manifolding several TCC units could possibly result in a quantity of flue gas large enough to improve economic justification for a CO boiler.

The carbon monoxide and hydrocarbons in reforming and desulfurization catalyst regeneration gases can be efficiently incinerated by passing the regeneration gases through a heater firebox. In some installations the sulfur dioxide is scrubbed by passing the regeneration gases through a packed water or caustic tower.

Wet- and Dry-Type, Centrifugal Dust Collectors

Cyclone separators are widely used for catalyst dust collection systems in refineries. They are located in the upper sections of both FCC unit

Table 176. TOTAL HYDROCARBON EMISSIONS FROM FLUID AND THERMOFOR CATALYTIC CRACKING UNIT STACKS[a] (Sussman, 1957)

Type	Mass spectrometer				Infrared spectrophotometer	
	Hydrocarbons	Hydrocarbons	Wt % C_1 and C_2	Vol % C_1 and C_2	Hydrocarbons (as hexane), tons/day	Hydrocarbons (as hexane), ppm
FCC	7.4	1,213	67.7	87.4	2.80	142
FCC	3.1	1,150	84.1	94.6	0.89	78
FCC	2.1	760	68.3	85.5	0.60	65
FCC[c]	1	98	42.3	54.1	0.30	12
TCC[e]	-	-	-	-	0.02	8
TCC[e]	-	-	-	-	0.02[h]	-
FCC[d,e]	-	-	-	-	1.20	116
TCC[d]	0.4	308	40.9	70.8	0.04	13
TCC[d]	0.5	4,484	55.1	81.4	0.15	43
TCC[b,c]	0.1	87	79.5	77	[g]	-
TCC[b,c]					0.02	14
TCC	0.5	121	67.4	67.8	[f]	-
TCC					0.02	9
FCC	0.3	328	51.2	75.3	-	Trace
TCC	1.4	1,655	61.9	18.8	0.30	108

[a]All concentrations are reported on a dry basis.
[b]Only the mass spectrometer results for Units F-2T and F-4T were reliable. Since Units F-1T and F-2T and Units F-3T and F-4T are twin units, the data shown result from combining the twin units.
[c]No methane present as determined by mass spectrometer.
[d]Mass spectrometer determinations include oxygenated C_4 and C_5 hydrocarbons.
[e]The mass spectrometer results were not reliable.
[f]The infrared spectrophotometer results were not reliable.
[g]Concentrations of hydrocarbons are below limit of accuracy of the infrared spectrophotometer.
[h]Infrared spectrophotometric determinations were made on Unit D-1T only. The results shown were obtained by assuming that twin Unit D-1T and D-2T emit the same quantity of hydrocarbons.

reactors and regenerators for collecting entrained catalyst. Some TCC units also use cyclones for catalyst fines collection from kiln regeneration gases. The cyclones are employed as a single unit or in multiple two-stage or three-stage series systems. Large FCC unit regenerators may have as many as 12 three-stage cyclones, while smaller units may have only 1 two-stage cyclone. In general, high-efficiency cyclones have dust collection efficiencies of over 90 percent for particle sizes of more than 15 microns. The efficiency drops off rapidly for particles of less than 10 microns.

Multiple cyclones are used in some cases for catalyst fines collection catalyst regeneration gases in TCC units. Dust collection efficiencies are in the same range as those for high-efficiency cyclones. Wet-type, centrifugal collectors or scrubbers adequately clean the gas streams from the catalyst elevators, and part of the regeneration gases from the kilns. Untreated water in the wet collector, however, can cause a carbonate deposit on the impeller, which is responsible for excessive wear on the collector bearings. This can and has resulted in excessive shutdown time for repairs. Table 180 shows particulate emissions from two wet-type, centrifugal catalyst dust collectors.

Electrical Precipitators

Many FCC units incorporate electrical precipitators for final collection of catalyst dust from catalyst regeneration gases. Electrical precipitators (see Figure 483) are normally installed in parallel systems because of the large volume of regeneration gases involved in FCC unit regenerators. Power requirements for these precipitators may range from 35 kva for small FCC units to 140 kva for the larger installations. The hot gases from the regenerator must be cooled from approximately 1,100° to below 500°F before entering the precipitator. This is accom-

Table 177. EMISSIONS OF SULFUR OXIDES, AMMONIA, AND CYANIDES FROM STACKS OF FLUID AND THERMOFOR CATALYTIC CRACKING UNITS[a] (Sussman, 1957)

Type	SO_3 lb/hr	SO_2, Chemical anal. lb/hr	SO_2, Chemical anal. ppm	SO_2, MS,[b] ppm	Totals as SO_2, vol %	Wt % SO_3 in total oxides of sulfur	NH_3, lb/hr	NH_3, ppm	Cyanides as HCN, Chemical anal. lb/hr	Cyanides as HCN, Chemical anal. ppm	Cyanides as HCN, MS,[b] ppm
FCC	164	535	438	47	0.055	23.5	130	401	0.250	0.48	430
FCC	12.0	362	512	220	0.540	3.2	27.0	140	0.280	0.94	360
FCC	1.20	1,260	2,190	1,850	0.220	0.1	20.5	134	Trace	Trace	240
FCC	8.90	453	308	20	0.031	1.8	26.0	67	0.291	0.47	170
TCC	1.25	17.5	114	-	0.011	6.7	1.20	29	0.010	0.15	-
TCC	-	-	-	-	-	-	-	-	-	-	-
FCC	6.90	648	984	-	0.098	1.1	118	675	0.054	0.19	-
TCC	5.10	15.1	86	19	0.011	25.0	4.60	99	0.005	0.07	370
TCC	2.0	14.0	65	10	0.008	13.0	3.40	60	0.060	0.70	230
TCC	1.60	18.7	151	-	0.016	7.9	2.20	67	Trace	Trace	-
TCC	2.70	13.2	136	91	0.016	17.0	1.90	74	Trace	Trace	90
TCC	5.74	13.0	105	-	0.015	30.6	1.56	47	Trace	Trace	-
TCC	7.77	11.1	97	60	0.015	41.2	3.12	103	Trace	Trace	180
FCC	3.07	205	1,310	360	0.130	1.4	23.0	550	0.018	0.27	190
TCC	0.62	24.4	141	15	0.014	2.5	2.80	61	0.039	0.54	220

[a]All concentrations are reported on a dry basis.
[b]MS = mass spectrophotometer.

Table 178. EMISSIONS OF ALDEHYDES, OXIDES OF NITROGEN, CO_2, O_2, CO, AND N_2 FROM STACKS OF FLUID AND THERMOFOR CATALYTIC CRACKING UNITS[a] (Sussman, 1957)

Type	Aldehydes as HCHO, lb/hr	Aldehydes as HCHO, ppm	NO_x as NO_2, lb/hr	NO_x as NO_2, ppm	NO by MS, ppm	CO_2, vol %, ORSAT	CO_2, vol %, MS	O_2, vol %, ORSAT	O_2, vol %, MS	CO, vol %, ORSAT	N_2, vol % by diff, ORSAT
FCC	77.0	130	26.0	29	250	8.7	11.1	5.1	2.2	4.9	81.0
FCC	18.0	53	4.2	8	-	8.5	8.8	3.5	4.1	7.8	80.2
FCC	25.9	96	163	394	160	10.0	11.8	2.3	2.3	6.1	81.6
FCC	4.0	5	202	191	11	13.4	13.4	2.0	2.3	0	84.6
TCC	3.5	49	5.7	51	-	8.2	-	7.9	-	1.4	82.5
TCC	-	-	-	-	-	-	-	-	-	-	-
FCC	0.9	3	5.9	12	-	9.5	-	2.7	-	6.8	81.0
TCC	2.2	26	0	0	200	9.2	12.1	6.6	-	3.2	81.0
TCC	1.2	12	0	0	170	4.7	9.0	13.5	-	0.7	81.1
TCC	0.6	12	3.1	34	-	9.6	-	8.3	-	1.5	80.6
TCC	0.4	9	2.2	32	190	12.8	13.3	2.5	2.5	3.6	81.1
TCC	2.6	44	2.7	30	-	8.4	-	9.8	-	0	81.6
TCC	3.4	63	0.6	7	130	8.8	9.2	7.8	11.1	2.6	80.8
FCC	1.5	20	-	-	310	7.8	7.8	5.1	5.5	6.1	81.0
TCC	14.3	177	7.7	62	230	9.0	9.0	6.9	7.3	4.1	80.0

[a]All concentrations are reported on a dry basis.

plished by a waste-heat boiler. The electrical conductivity of the gas stream may be increased by injecting ammonia upstream of the precipitator.

The inlet ducting is designed to effect a uniform gas distribution through the precipitator cross section. A perforated-plate inlet or vane section assists in accomplishing the desired distribution.

The precipitators usually employ either a continuous-type electrode-rapping and plate-vibrating sequence or an intermittent hourly rapping cycle. A dust plume up to 90 percent opacity arises for a period of 1 to 2 minutes from the precipitator's discharge stack during the intermittent hourly rapping cycle. This high-opacity, short-interval plume is not normally encountered with the continuous rapping sequence.

Table 179. MOISTURE AND FLUE GAS VOLUMES, %, FROM STACKS OF FLUID AND THERMOFOR CATALYTIC CRACKING UNITS (Sussman, 1957)

Type	Vol % H_2O as determined from sampling trains	Vol % H_2O in MS[a] sample	Rate of flow of flue gases (wet basis), scfm	Rate of flow of flue gases (dry basis), scfm
FCC	19.7	0.480	151,000	121,300
FCC	19.2	0.470	86,300	69,700
FCC	26.3	0.186	77,200	56,900
FCC	18.7	0.229	178,800	145,400
TCC	12.1	-	17,300	15,200
TCC	-	-	20,800	-
FCC	18	-	80,900	65,000
TCC	16.5	0.626	20,700	17,280
TCC	11.1	2.448	23,600	20,980
TCC	12.2	-	13,970	12,270
TCC	19	0.885	11,660	9,600
TCC	11	-	13,800	12,300
TCC	11	0.600	12,700	11,300
FCC	25.3	0.458	20,800	15,540
TCC	7.5	1.762	18,400	17,000

[a]MS = mass spectrophotometer.

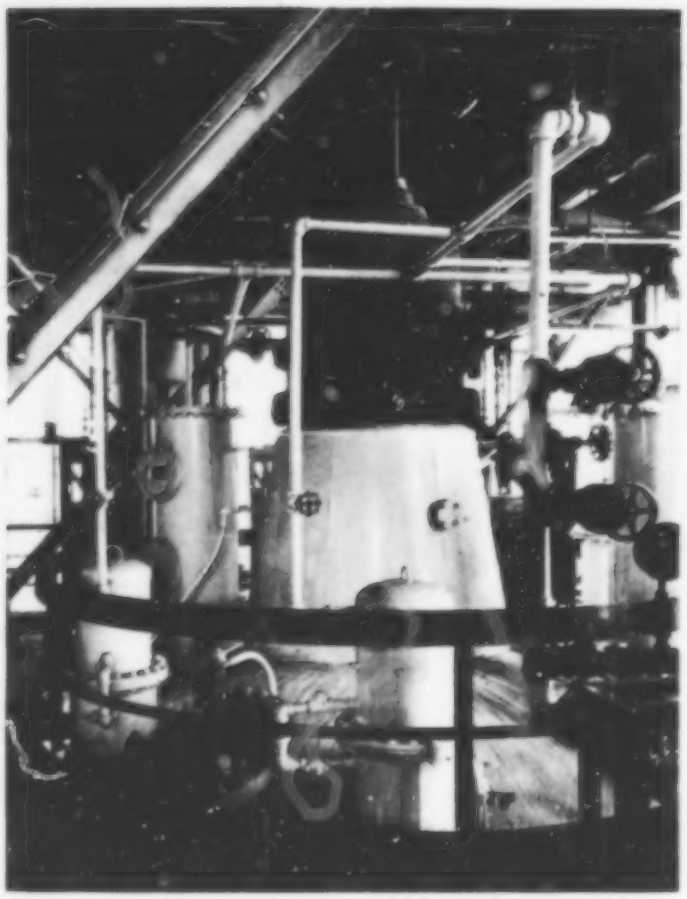


Figure 483. Top of fluid catalytic cracking unit's Cottrell precipitator. Electrode terminals and 36-inch-diameter flue gasline between precipitator and silencer are shown (Union Oil Company of California, Los Angeles, Calif.).

Carbon Monoxide Waste-Heat Boilers

Large amounts of carbon monoxide gases are discharged to the atmosphere with the regeneration flue gases of an FCC unit. The carbon monoxide waste-heat boiler is a means of using the heat of combustion of carbon monoxide and other combustible, and the sensible heat of the regeneration gases. From the air pollution viewpoint, the CO boiler oxidizes the carbon monoxide and other combustibles, mainly hydrocarbons, to carbon dioxide and water.

In most cases, auxiliary fuel is required in addition to the carbon monoxide and may be either fuel oil, refinery process gas, or natural gas. The CO boiler may be a vertical structure with either a rectangular or circular cross section with water-cooled walls, as shown in Figure 484. The outer dimensions of a typical rectangular boiler are 32 feet wide by 44 feet deep by 64 feet high, with a 200-foot-high stack. The boiler is equipped with a forced-draft fan and four sets of fixed, tangential-type burners (one set for each corner). A typical set of burners includes two carbon monoxide gas compartments, four fuel gas nozzles, and two steam-atomized oil burners, as shown in Figure 485. The burners are approximately 1-1/2 feet wide by 6 feet high. A tangential-type mixing of the gases for more nearly complete combustion is achieved by arranging the burners slightly off center.

Table 180. EMISSIONS FROM WET-TYPE, CENTRIFUGAL CATALYST DUST COLLECTORS (THERMOFOR CATALYTIC CRACKING UNIT)[a]

	Collector No. 1 with two inlet streams		Collector No. 2 with two inlet streams	
	TCC No. 1	TCC No. 2	TCC No. 3	TCC No. 4
Inlet gas volume, scfm	1,780	2,090	2,350	1,680
Inlet gas temperature, °F	720	690	740	650
Inlet gas H_2O content, vol %	38.8	39.3	27.6	22.1
Particulate matter, lb/hr	31.7	40.1	23.2	52.0
	Collector No. 1 discharge		Collector No. 2 discharge	
Outlet gas volume, scfm	4,230		5,090	
Outlet gas temperature, °F	210		210	
Outlet gas H_2O content, vol %	41.2		30.4	
Particulate loss, lb/hr	10.2		8.6	
Collection efficiency, %	85.8		88.6	

[a] The inlet of each collector is connected by ductwork to the reactor elevator and the Thermofor kiln of two Thermofor catalytic cracking units.

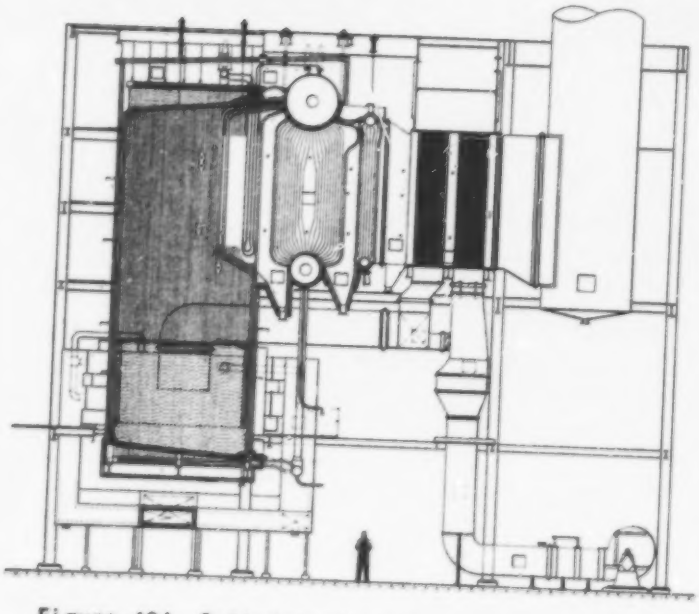


Figure 484. Cylindrical, water-cooled, carbon monoxide waste-heat boiler (Combustion Engineering, Inc., Windsor, Conn.).

Regeneration gases from the FCC unit are normally delivered to the inlet of the CO boiler ductwork at about 1,100°F and 2 psig. Whenever the overhead regenerator gases first pass through an electrical precipitator, the inlet gas to the precipitator must be cooled below 500°F. The CO boiler would then receive regeneration flue gas between 450° and 500°F.

The main reactions of the CO boiler's firebox include burning the refinery gas or fuel oil to carbon dioxide and water and completing the oxidation of the carbon monoxide. Other reactions include oxidation of the sulfur compounds in the fuel oil or refinery gas to sulfur dioxide. The small amount of ammonia in the regeneration flue gas is primarily converted to oxides of nitrogen at the firebox temperature of between 1,800° and 2,000°F. Table 181 shows the emissions from an FCC unit's CO boiler.

Economic Considerations

The economics of a CO boiler installation can be generalized sufficiently to determine a range of catalytic cracking unit sizes that can pay out a boiler (Alexander and Bradley, 1958). The main variable used in determining the size of the catalytic cracking unit is coke-burning rate. Other variables that affect payout include the following in the order of decreasing importance: (1) Fuel value, (2) CO_2/CO ratio, (3) flue gas temperatures, (4) excess oxygen in CO gas, (5) hydrogen content of regenerator coke.

On the assumption that additional steam is required in the refinery, a coke burnoff rate of 10,000 pounds per hour or more can be economically attractive for installation of a CO boiler when the fuel has a value of 20 cents per million Btu. If, however, additional steam is not required, the minimum coke-burning rate to provide a reasonable payout for a CO boiler is about 18,000 pounds per hour. A payout of 6 years after taxes is assumed to be an attractive investment. In some areas, the reduction in the air contaminants is sufficiently important to justify a payout longer than 6 years.

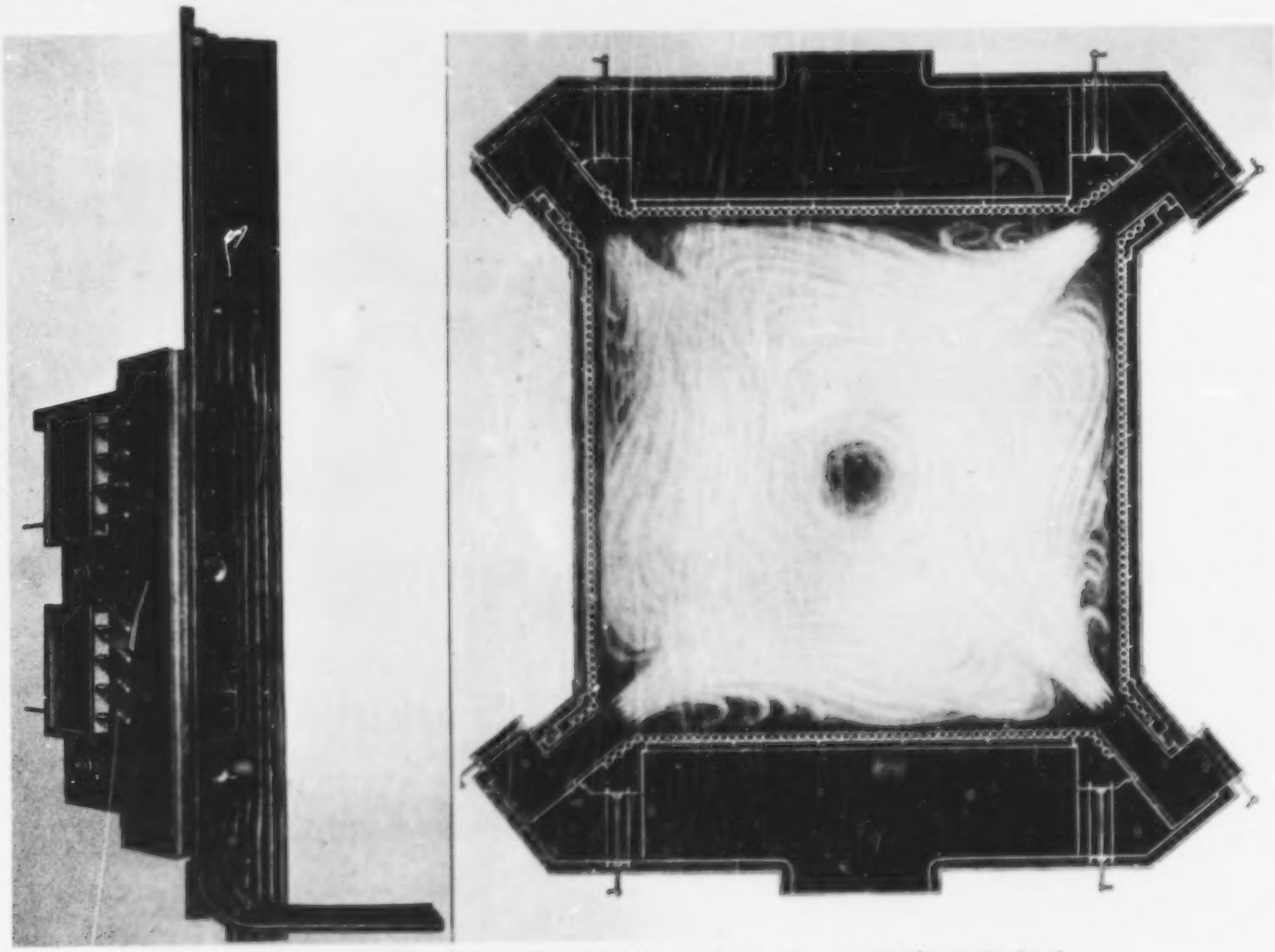


Figure 485. Corner-fired burners of a carbon monoxide waste-heat boiler: (left) Elevation view showing a typical set of burners for one corner; (right) plan view of firebox showing location of the four sets of burners (Combustion Engineering, Inc., Windsor, Conn.).

Table 181. EMISSIONS FROM THE STACKS OF FLUID CATALYTIC CRACKING UNITS' CARBON MONOXIDE WASTE-HEAT BOILERS[a]

	Unit I		Unit II
	East stack	West stack	
Gas volume, scfm	96,800	97,200	60,700
Gas temperature, °F	470	450	570
Dust loss, lb/hr	44	33	34.9
NO_x as NO_2, ppm	173	190	67
Aldehydes as HCHO, ppm	15	11	5
NH_3, lb/hr	19.8	22.5	None[b]
SO_2, lb/hr	269	282	265
SO_3, lb/hr	0.16	0.4	1.61
Organic acids as acetic, ppm	-	-	11.7
Hydrocarbons as C_6, ppm	None	None	< 8
CO_2, vol % dry basis	14	14.4	8.8
CO, vol % dry basis	0	0	0
O, vol % dry basis	3	2.6	3.5
H_2O, vol %	22.4	22.7	23.9

[a] Both FCC Units I and II are equipped with electrostatic precipitators.
[b] FCC Unit II does not use NH_3 injection for precipitator conditioning.

OIL-WATER EFFLUENT SYSTEMS

FUNCTIONS OF SYSTEMS

Oil-water effluent systems are found in the three phases of the petroleum industry--production, refining, and marketing. The systems vary in size and complexity though their basic function remains the same, that is, to collect and separate wastes, to recover valuable oils, and to remove undesirable contaminants before discharge of the water to ocean, rivers, or channels.

Handling of Crude-Oil Production Effluents

In the production of crude oil, wastes such as oily brine, drilling muds, tank bottoms, and free oil are generated. Of these, the oilfield brines present the most difficult disposal problem because of the large volume encountered

(Rudolfs, 1953). Community disposal facilities capable of processing the brines to meet local water pollution standards are often set up to handle the treatment of brines. The most effective method of disposal of brines has been injection into underground formations.

A typical collection system associated with the crude-oil production phase of the industry usually includes a number of small gathering lines or channels transmitting waste water from wash tanks, leaky equipment, and treaters to an earthen pit, a concrete-lined sump, or a steel waste-water tank. A pump decants waste water from these containers to water-treating facilities before injection into underground formations or disposal to sewer systems. Any oil accumulating on the surface of the water is skimmed off to storage tanks.

Handling of Refinery Effluents

The effluent disposal systems found in refineries are larger and more elaborate than those in the production phase. A typical modern refinery gathering system usually includes gathering lines, drain seals, junction boxes, and channels of vitrified clay or concrete for transmitting waste water from processing units to large basins or ponds used as oil-water separators. These basins are sized to receive all effluent water, sometimes even including rain runoff, and may be earthen pits, concrete-lined basins, or steel tanks.

Liquid wastes discharging to these systems originate at a wide variety of sources such as pump glands, accumulators, spills, cleanouts, sampling lines, relief valves, and many others. The types of liquid wastes may be classified as waste water with:

1. Oil present as free oil, emulsified oil, or as oil coating on suspended matter;

2. chemicals present as suspensoids, emulsoids, or solutes. These chemicals include acids, alkalies, phenols, sulfur compounds, clay, and others.

Emissions from these varied liquid wastes can best be controlled by properly maintaining, isolating, and treating the wastes at their source; by using efficient oil-water separators; and by minimizing the formation of emulsions. Recovery of some of the wastes as valuable byproducts is growing in importance.

Treatment of Effluents by Oil-Water Separators

The waste water from the process facilities and treating units just discussed flows to the oil-water separator for recovery of free oil and settleable solids.

The American Petroleum Institute is recognized as an authoritative source of information on the design of oil-water separators, and its recommended methods are used generally by refineries in Los Angeles County. The basis for design of a separator is the difference in gravity of oil and water. A drawing of a typical separator is shown in Figure 486.

Factors affecting the efficiency of separation include temperature of water, particle size, density, and amounts and characteristics of suspended matter. Stable emulsions are not affected by gravity-type separators and must be treated separately.

The oil-water separator design must provide for efficient inlet and outlet construction, sediment collection mechanisms, and oil skimmers. Reinforced concrete construction has been found most desirable for reasons of economy, maintenance, and efficiency.

Clarification of Final-Effluent Water Streams

The effluent water from the oil-water separator may require further treatment before final discharge to municipal sewer systems, channels, rivers, or streams. The type and extent of treatment depend upon the nature of the contaminants present, and on the local water pollution ordinances governing the concentration and amounts of contaminants to be discharged in refinery effluent waters. The methods of final-effluent clarification to be briefly discussed here include (1) filtration, (2) chemical flocculation, and (3) biological treatment.

Several different types of filters may be used to clarify the separator effluent. Hay-type filters, sand filters, and vacuum precoat filters are the most common. The selection of any one type depends upon the properties of the effluent stream and upon economic considerations.

The application of chemical flocculation to the treatment of separator effluent water is a relatively recent development (Reno et al., 1958; Castler et al., 1956). Methods of treatment are either by sedimentation or flotation. In sedimentation processes, chemicals such as copper sulfate, activated silica, alum, and lime are added to the waste-water stream before it is fed to the clarifiers. The chemicals cause the suspended particles to agglomerate and settle out. Sediment is removed from the bottom of the clarifiers by mechanical scrapers.

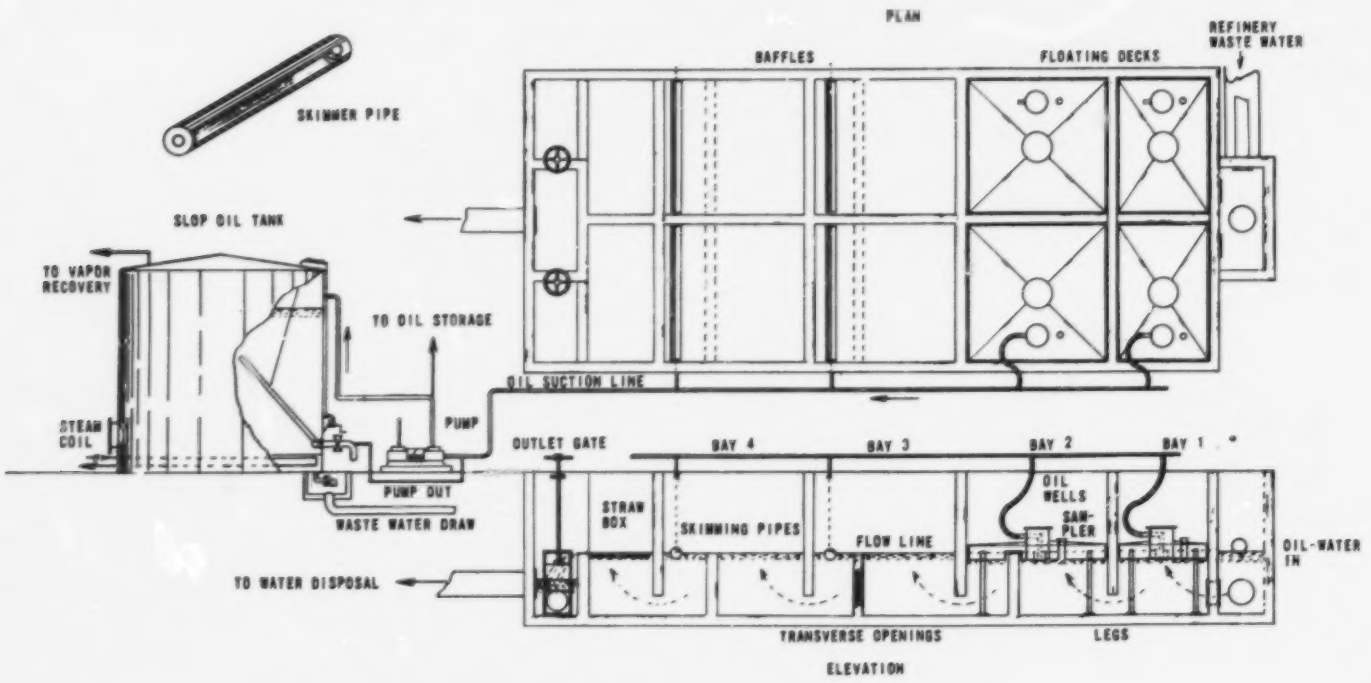


Figure 486. A modern oil-water separator.

Effectiveness of the sedimentation techniques in the treatment of separator effluents is limited by the small oil particles contained in the waste water. These particles, being lighter than water, do not settle out easily. They may also become attached to particles of suspended solids and thereby increase in buoyancy.

In the flotation process a colloidal floc and air under pressure are injected into the waste water. The stream is then fed to a clarifier through a backpressure valve that reduces the pressure to atmospheric. The dissolved air is suddenly released in the form of tiny bubbles that carry the particles of oil and coalesced solids to the surface where they are skimmed off by mechanical flight scrapers. Of the two, the flotation process has the potential to become the more efficient and economical.

Biological treating units such as trickling filters activated-sludge basins, and stabilization basins have been incorporated into modern refinery waste disposal systems. By combining adsorption and oxidation, these units are capable of reducing oil, biological oxygen demand, and phenolic content from effluent water streams. To prevent the release of air pollutants to the atmosphere, certain pieces of equipment, such as clarifiers, digesters, and filters, used in biological treatment should be covered and vented to recovery facilities or incinerated.

Effluent Wastes From Marketing Operations

In the marketing and transportation phase of the industry, waste water containing oil may be discharged during the cleaning of ballast tanks or ships, tank trucks, and tank cars. Leaky valves and connections and flushing of pipelines are other sources of effluents. The methods used for treatment and disposal of these waters are similar to those used in the other phases of the industry.

THE AIR POLLUTION PROBLEM

From an air pollution standpoint the most objectionable contaminants emitted from liquid waste streams are hydrocarbons, sulfur compounds, and other malodorous materials.

The effect of hydrocarbons in smog-producing reactions is well known, and sulfur compounds such as mercaptans and sulfides produce very objectionable odors, even in high dilution. These contaminants can escape to the atmosphere from openings in the sewer system, open channels, open vessels, and open oil-water separators. The large exposed surface area of these separators requires that effective means of control be instituted to minimize hydrocarbon losses to the atmosphere from this source. A method (Jones and Viles, 1952) developed by personnel of Humble Oil and Refining Company may be used to estimate the hydrocarbon losses from

open oil-water separators. In the development of this method the principal variables that influence evaporation rates were assumed to be vapor pressure of the oil, and wind velocity. Experimental work was done to observe and correlate the effects of these factors on evaporation rates. From the data compiled, a procedure for calculation of losses was devised. Essentially, this procedure is as follows:

1. Obtain a representative sample of oil at the surface of the separator.

2. Obtain the vapor pressure of the sample and the average wind velocity at the surface of the separator.

3. Using Figure 487, find the loss in bbl/day per ft^2.

4. Since the data compiled were collected under ideal conditions, a correlation factor is needed to correct the value ob tained from Figure 487 to actual separator conditions. This correlation factor may be found by measuring the evaporation rate of a weighted sample of a constantly boiling hydrocarbon from a shallow vessel placed on the surface of the separator. The correlation factor is then calculated as the ratio of the measured rate of evaporation to the theoretical evaporation rate from Figure 487.

5. The product of the theoretical separator loss, the correlation factor, and the separator area represents the total evaporation loss.

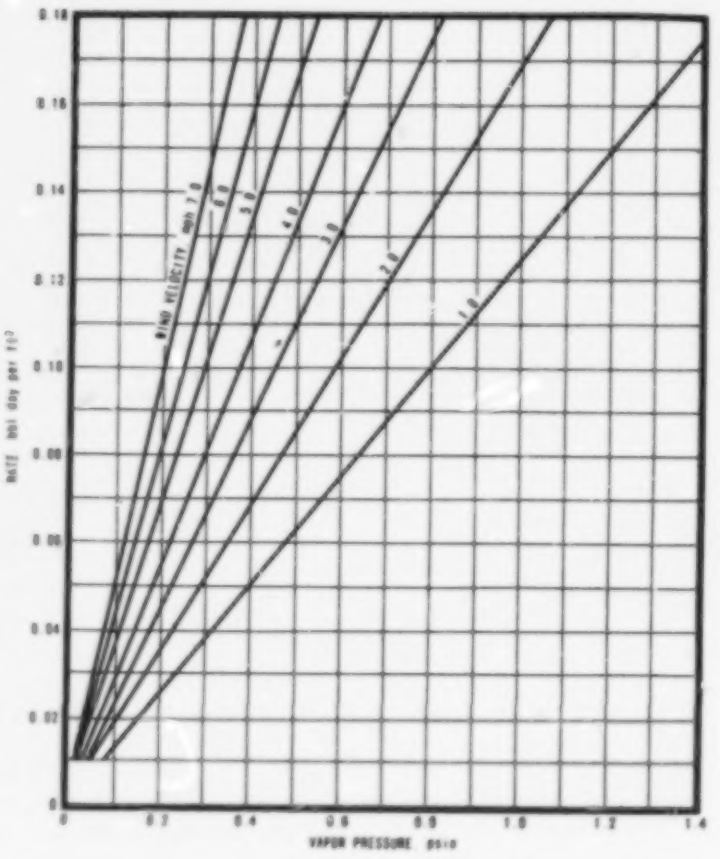


Figure 487. Relationship of laboratory evaporation rates for various wind velocities to vapor pressure of oil (Jones and Viles, 1952).

AIR POLLUTION CONTROL EQUIPMENT

Hydrocarbons From Oil-Water Separators

The most effective means of control of hydrocarbon emissions from oil-water separators has been the covering of forebays or primary separator sections. Either fixed roofs or floating roofs (Brown and Sublett, 1957) are acceptable covers. Separation and skimming of over 80 percent of the flotable oil layer is effected in the covered sections. Thus, only a minimum of oil is contained in the effluent water, which flows under concrete curtains to the open afterbays or secondary separator sections.

Satisfactory fixed roofs have been constructed by using wooden beams for structural support, and asbestos paper as a cover. A mastic-type sealing compound is then used to seal all joints and cracks. Although this form of roof is acceptable for the control of pollutants, in practice, making the roof completely vaportight is difficult. The resultant leakage of air into the vapor space, and vapor leakage into the atmosphere are not desirable from standpoints of air pollution or safety. For example, an explosive mixture resulting from leakage of air from gaging operations into the vapor space of a fixed-roof separator at a Los Angeles refinery was ignited by a static electric spark. The destruction of the wooden roof has emphasized the need for elimination of the vapor space. Another type of enclosed separator with a concrete cover and gas blanketing of the vapor space has proved satisfactory. The effluent vapors from this system are vented to vapor recovery.

The explosion hazard associated with fixed roofs is not present in a floating-roof installation. These roofs are similar to those developed for storage tanks. The floating covers are built to fit into bays with about 1 inch of clearance around the perimeter. Fabric or rubber may be used to seal the gap between the roof edge and the container wall. The roofs are fitted with access manholes, skimmers, gage hatches, and supporting legs. Floating roofs on refinery separators are shown in Figures 488 and 489. In operation, skimmed oil flows through lines from the skimmers to a covered tank (floating roof or connected to vapor recovery) or sump and then is pumped to de-

Figure 488. Floating-roof cover on refinery oil-water separator (Union Oil Company of California, Los Angeles, Calif.).

emulsifying processing facilities. Effluent water from the oil-water separator is handled in the manner described previously.

In addition to covering the separator, open sewer lines that may carry volatile products are converted to closed, underground lines with water-seal-type vents. Junction boxes are vented to vapor recovery facilities, and steam is used to blanket the sewer lines to inhibit formation of explosive mixtures.

Accurate calculation of the hydrocarbon losses from separators fitted with fixed roofs is difficult because of the many variables of weather and refinery operations involved. One empirical equation that has been used with reasonable success to calculate losses from separators is

$$w = \frac{AdHm}{(12)(379)} \qquad (136)$$

where

w = weight of hydrocarbon loss, lb/hr

A = area of covered separator, ft^2

d = depth of vapor space, in.

H = vol % of hydrocarbons as hexane in the vapor space

m = molecular weight of hexane.

In using this equation, assume that the density of condensed vapors (C_6H_{14}) equals 5.5 pounds per gallon and that the vapor in the separator is displaced once per hour. The vapor concentration is determined by using the average of readings from a calibrated explosion meter over the entire covered area. The assumption that the vapors are displaced once every hour was determined by using data from work done by the Pacific Coast Gas Association (Powell, 1950).

The previously discussed methods of obtaining emissions from uncovered separators may also be applied to sections covered with fixed roofs. Use of more than one method and a number of tests of one source over a considerable period of time are necessary to ensure an acceptable estimate of emissions.

Emissions from separators fitted with floating-roof covers may be assumed to be almost negligible. A rough approximation of the magnitude of the emission can be made by assuming the emission to be from a floating-roof storage tank of

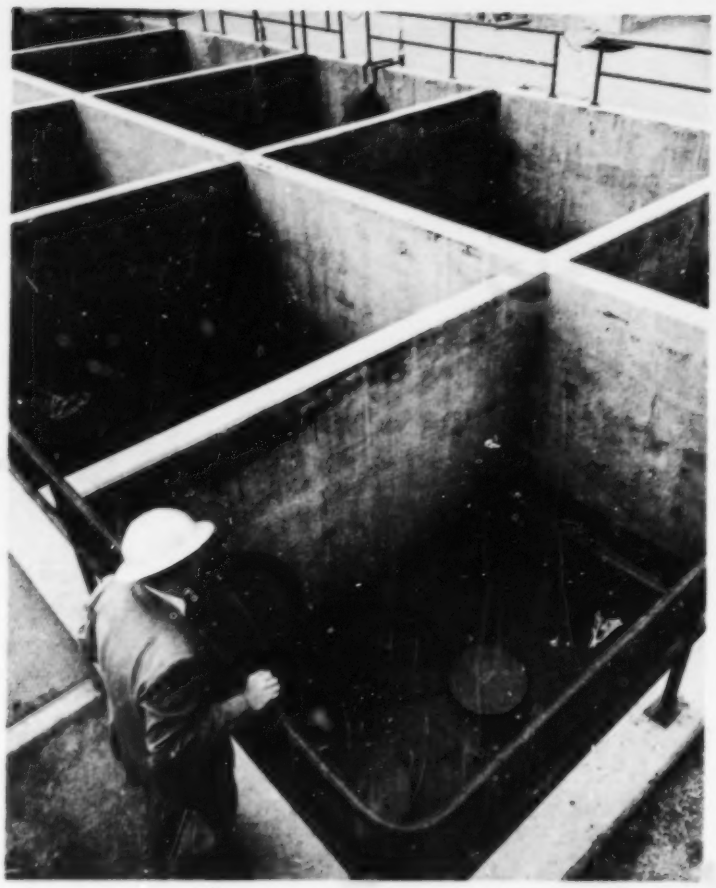


Figure 489. Floating roof on refinery oil-water separator (Atlantic-Richfield Oil Company, Los Angeles, Calif.).

equivalent perimeter. The API method of calculating losses from storage tanks can then be applied.

Treatment of Refinery Liquid Wastes at Their Source

Isolation of certain odor- and chemical-bearing liquid wastes at their source for treatment before discharge of the water to the refinery wastewater-gathering system has been found to be the most effective and economical means of minimizing odor and chemicals problems. The unit that is the source of wastes must be studied for possible changes in the operating process to reduce wastes. In some cases the wastes from one process may be used to treat the wastes from another. Among the principal streams that are treated separately are oil-in-water emulsions, sulfur-bearing waters, acid sludge, and spent caustic wastes.

Oil-in-Water Emulsions

Oil-in-water emulsions are types of wastes that can be treated at their source. An oil-in-water emulsion may be defined as a suspension of oil particles in water that cannot be divided effectively by means of gravity alone. Gravity-type oil-water separators are, in most cases, ineffective in breaking the emulsions, and means are provided for separate treatment where the problem is serious.

Oil-in-water emulsions are objectionable in the drainage system since the separation of otherwise recoverable oil may be impaired by their presence. Moreover, when emulsions of this type are discharged into large bodies of water, the oil is released by the effect of dilution, and serious pollution of the water may result.

Formation of emulsions may be minimized by proper design of process equipment and piping. Several methods, both physical and chemical, are available for use in breaking emulsions. Physical methods of separation include direct application of heat, distillation, centrifuging, filtration, and use of an electric field. The effectiveness of any one method depends upon the type of emulsion to be treated. Chemical methods of separation are many and varied. During recent years the treatment of waste water containing emulsions with coagulating chemicals has become increasingly popular.

Variations of this form of treatment include air flotation systems, and biological treatment of the waste water, as discussed previously in this section.

Sulfur-bearing waters

Sulfides and mercaptans are removed from wastewater streams by various methods. Some refineries strip the waste water in a column with live steam. The overhead vapors from the column are condensed and collected in an accumulator from which the noncondensables flow to sulfur-recovery facilities or are incinerated. One Los Angeles refinery removes all the hydrogen sulfide and about 90 percent of the ammonia from a waste stream by this method. Flue gas has also been used successfully as the stripping medium in pilot-plant studies. Bottoms water from steam-stripping towers, being essentially sulfide free, can then be drained to the refinery's sewer system.

Oxidation of sulfides in waste water is also an effective means of treatment (Smith, 1956a). Air and heat are used to convert sulfides and mercaptans to thiosulfates, which are water soluble and not objectionable. Figure 490 depicts the flow through an air oxidation unit. Experience has shown that, under certain conditions, the thiosulfates may be reduced by the action of Vibrio desulfuricans bacteria, which results in

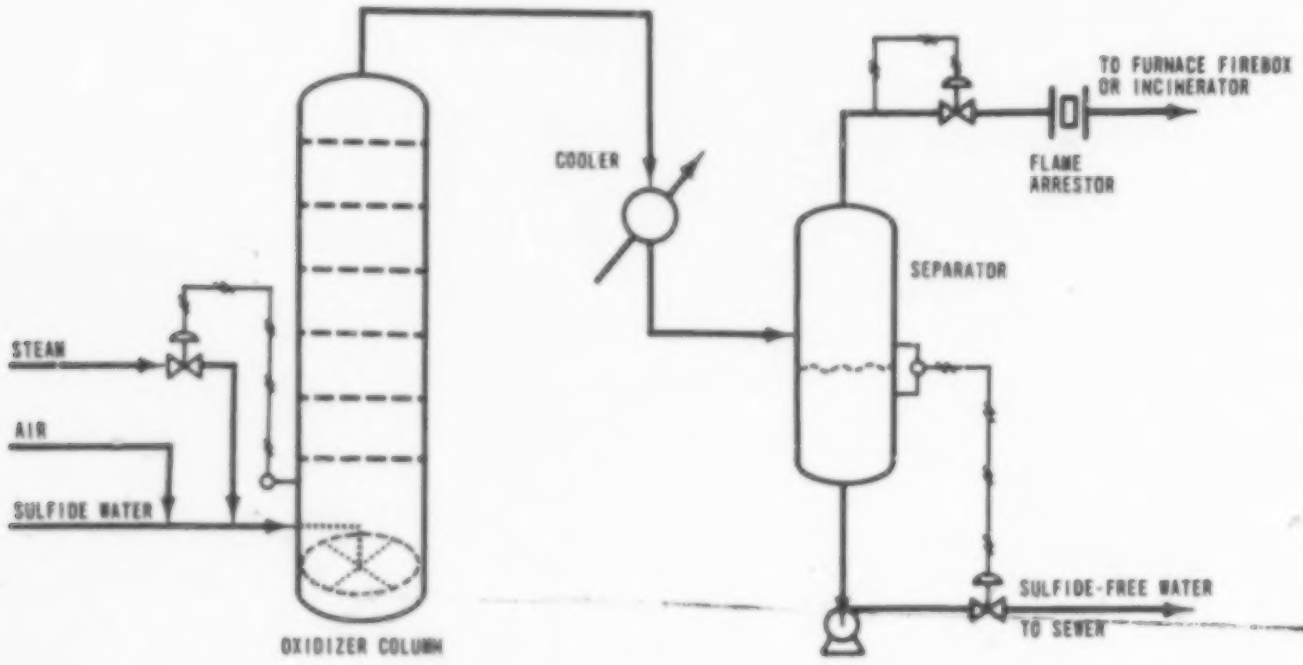


Figure 480. Flow diagram of air oxidation process (Smith, 1956b).

the release of hydrogen sulfide. The reduction takes place only in the absence of dissolved oxygen. Care must be used to keep this water from entering retention sumps or pits subject to this bacterial attack.

Chlorine is also used as an oxidizing agent for sulfides. It is added in stoichiometric quantities proportional to the waste water. This method is limited by the high cost of chlorine. Water containing dissolved sulfur dioxide has been used to reduce sulfide concentration in waste waters. For removing small amounts of hydrogen sulfide, copper sulfate and zinc chloride have been used to react and precipitate the sulfur as copper and zinc sulfides. Hydrogen sulfide may be released, however, if the water treated with these compounds contacts an acid stream.

Acid sludge

The acid sludge produced from treating operations varies with the stock treated and the conditions of treatment. The sludge may vary from a low-viscosity liquid to a solid. Methods of disposal of this sludge are many and varied. Basically, they may be considered under three general headings:

1. Disposal by burning as fuel, or dumping in the ground or at sea;
2. processing to produce byproducts such as ammonium sulfate, metallic sulfates, oils, tars, and other materials;
3. processing for recovery of acid.

The burning of sludge results in discharge to the atmosphere of excessive amounts of sulfur dioxide and sulfur trioxide from furnace stacks. This latter consideration has caused the discontinuance of this method of disposal in Los Angeles County. If sludge is solid or semisolid it may be buried in specially constructed pits. This method of disposal, however, creates the problem of acid leaching out to adjacent waters. Dumping in designated sea areas eliminates pollution of the potable waters and atmosphere of populated areas.

Recovery of sulfuric acid from sludge is accomplished essentially by either hydrolysis or thermal decomposition processes. Sulfuric acid sludge is hydrolyzed by heating it with live steam in the presence of water. The resulting product separates into two distinct phases. One phase consists of diluted sulfuric acid with a small amount of suspended carbonaceous material, and the second phase, of a viscous acid-oil layer. The dilute sulfuric acid may be (1) neutralized by alkaline wastes, (2) reacted chemically with ammonia-water solution to produce ammonium sulfate for fertilizer, or (3) concentrated by heating.

Acid sludge may be decomposed by heating to 300°F to form coke, sulfur dioxide, oil, water, and lighter boiling hydrocarbons as a gas. Several commercial decomposition processes have been developed to use the sulfur present in the sludge. In all these processes a kiln is used wherein the sludge is mixed with hot coke or some other carrying agent and heated to the required temperature. Another process allows the acid sludge to be burned directly. The sulfur dioxide gases from the reaction are purified and then either converted to sulfuric acid (contact process) or to free elemental sulfur. The tail gases emitted from these decomposition processes may create an odor nuisance as well as cause damage to vegetation in the surrounding area. Because of this, the tail gases may require additional treatment to preclude the possibility of a nuisance.

Of all the methods discussed, hydrolysis and decomposition are the most desirable from the standpoint of air pollution control, though they are not the most economical when the volume of acid is small.

Spent caustic wastes

Caustic soda is widely used in the industry to neutralize acidic materials found in crude oil and its fractions. It is also used to remove mercaptans, naphthenates, or cresols from gas, gasoline, kerosene, and other product streams. The resulting spent caustic is imbued with the odors of the compounds that have been extracted in the various treating processes (American Petroleum Institute, 1969). This spent caustic can be a source of intense objectionable odors and can result in nuisance complaints.

Spent caustic is treated by direct methods or chemical processing, or both. Direct methods of disposal include ponding, dilution, disposal wells, and sale. Of these, ponding is not recommended, since the pond could become a source of air pollutants as well as a possible source of contamination of underground water through seepage. Dilution of spent caustic in large bodies of water is a commonly used method of disposal. The ocean and brackish waters are the only desirable areas for this disposal, to preclude pollution of fresh-water streams.

Disposal wells afford another convenient means of disposing of spent-caustic solutions, provided that local conditions are favorable. The method consists of pumping the liquid wastes into underground formations that contain saline or nonpotable water. Spent caustics that contain phenolates, cresolates, and sulfides may be sold outside the industry for recovery of these materials.

In addition to these direct methods of disposal, chemical processing methods are available. These include neutralization, combination of neutralization and oxidation, and combination of oxidation and chemical separation.

Neutralization of high-alkaline caustic wastes may be effected by means of spent acids from other refinery operations. After neutralization, the resulting salt solution may be suitable for discharge into the refinery's drainage system. In some cases odorous or oily materials may have to be stripped from the product before discharge. In these instances effluent gases should be incinerated.

Spent-caustic solutions can also be neutralized with acid gases such as flue gases (Fisher and Moriarty, 1953). Oxygen contained in the flue gas tends to oxidize sulfides and mercaptides as a secondary reaction. Effluent gases from this reaction must be properly incinerated to prevent odor problems. The resulting treated solution contains carbonates, bicarbonates, thiosulfates, sulfates, and sulfites and may be suitable for discharge into the drainage system.

A recently developed method of treating caustic wastes involves the addition of pickling acid. The acid is mixed with caustic and is airblown. The resulting solution is filtered and naphtha is added to extract organic acids for recovery. Fumes from the airblowing operation must be incinerated. The treated salt solution is discharged to a drainage system.

PUMPS

TYPES OF PUMPS

Pumps are used in every phase of the petroleum industry. Their applications range from the lifting of crude oil from the depths of a well to the dispensing of fuel to automobile engines. Leakage from pumps can cause air pollution wherever organic liquids are handled.

Pumps are available in a wide variety of models and sizes. Their capacities may range from several milliliters per hour, required for some laboratory pumps, to 3/4 million gallons per minute, required of each of the new pumps at Grand Coulee Dam (Dolman, 1952).

Materials used for construction of pumps are also many and varied. All the common machinable metals and alloys, as well as plastics, rubber,

and ceramics, are used. Pumps may be classified under two general headings, positive displacement and centrifugal.

Positive-Displacement Pumps

Positive-displacement pumps have as their principle of operation the displacement of the liquid from the pump case by reciprocating action of a piston or diaphragm, or rotating action of a gear, cam, vane, or screw. The type of action may be used to classify positive-displacement pumps as reciprocating or rotary. Figures 491 and 492 depict some typical pumps of each type. When a positive-displacement pump is stopped, it serves as a check valve to prevent backflow.

Centrifugal Pumps

Centrifugal pumps operate by the principle of converting velocity pressure generated by centrifugal force to static pressure. Velocity is imparted to the fluid by an impeller that is rotated at high speeds. The fluid enters at the center of the impeller and is discharged from its periphery. Unlike positive-displacement pumps, when the cen-

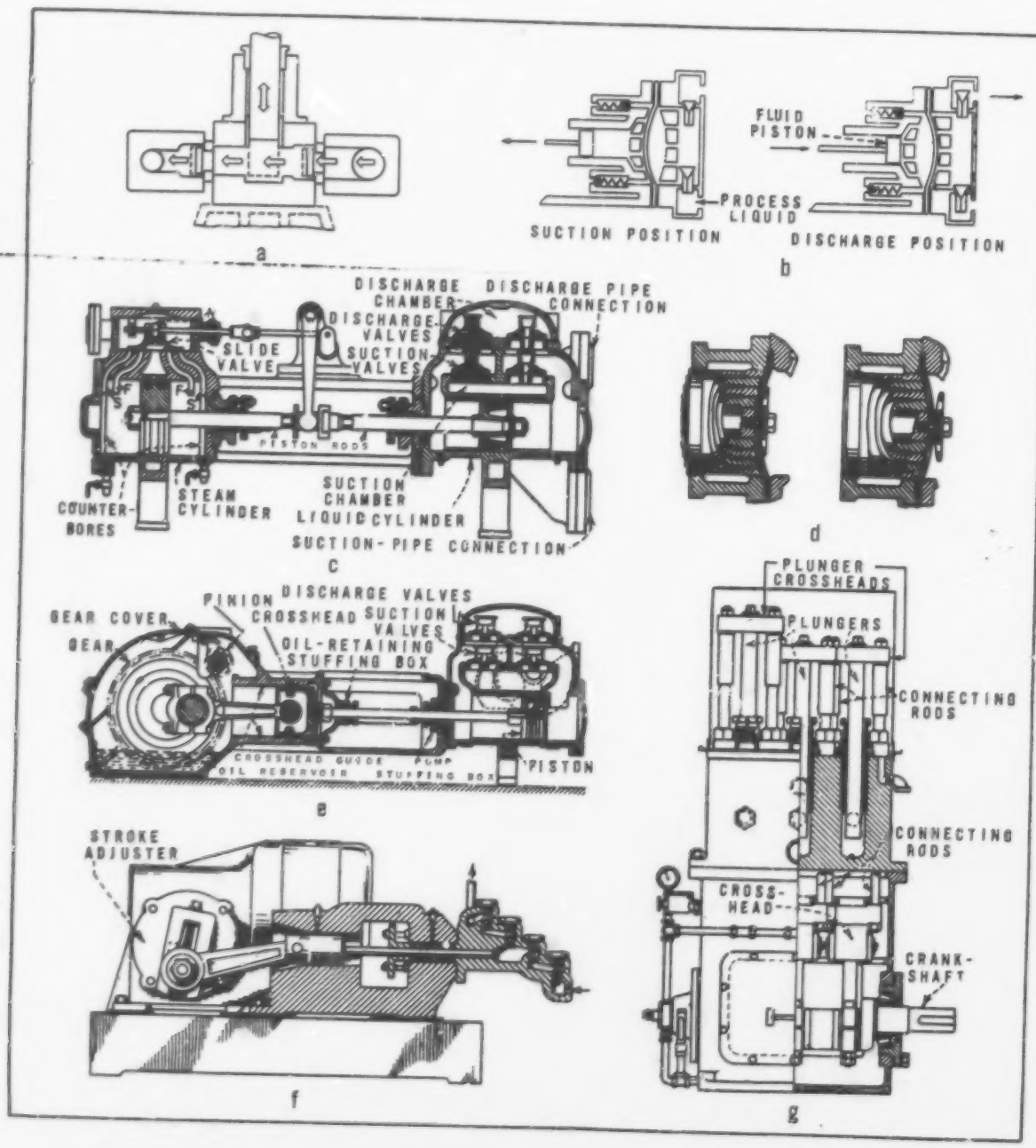


Figure 491. Reciprocating pumps: (a) Principle of reciprocating pump, (b) principle of fluid-operated diaphragm pump, (c) direct-acting steam pump, (d) principle of mechanical diaphragm pump, (e) piston-type power pump, (f) plunger-type power pump with adjustable stroke, (g) inverted, vertical, triplex power pump (Dolman, 1952).

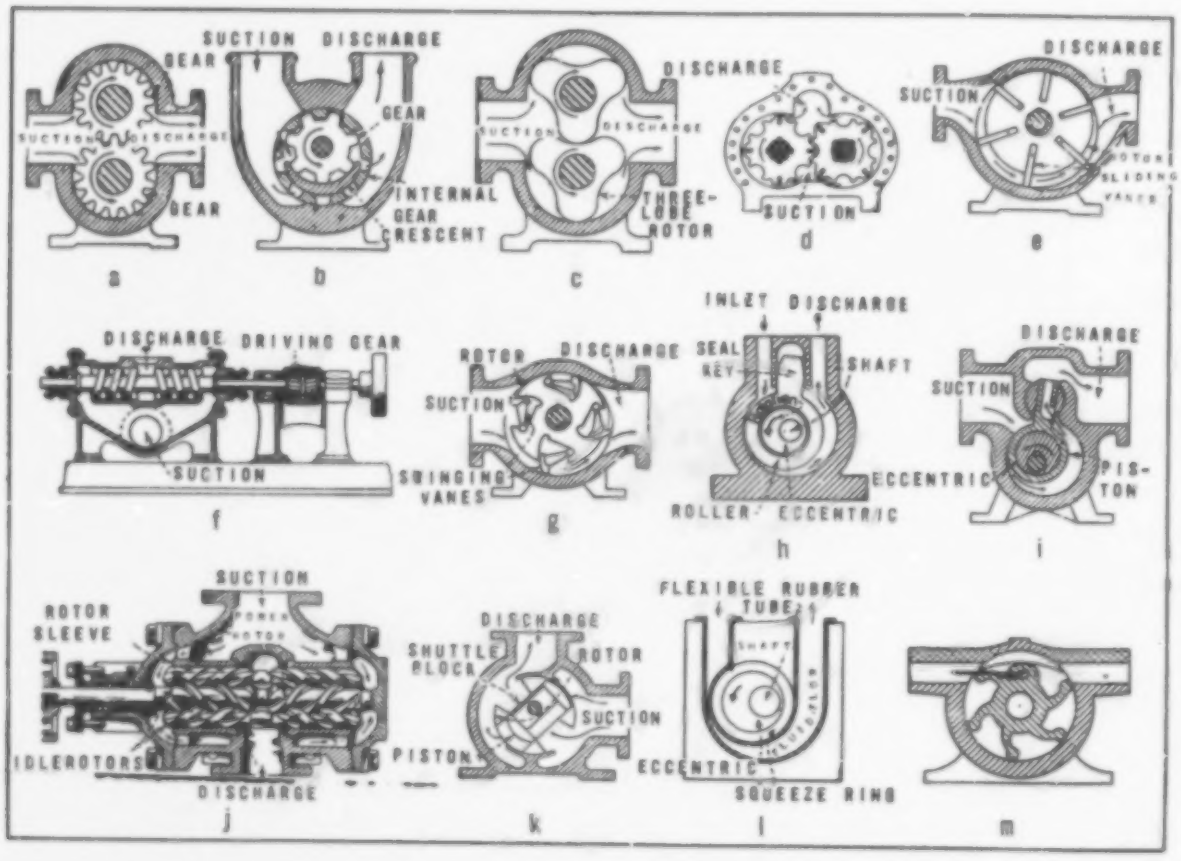


Figure 492. Rotary pumps: (a) External-gear pump, (b) internal-gear pump, (c) three-lobe pump, (d) four-lobe pump, (e) sliding-vane pump, (f) single-screw pump, (g) swinging-vane pump, (h) cam or roller pump, (i) cam-and-piston pump, (j) three-screw pump; (k) shuttle-block pump, (l) squeegee pump, (m) neoprene vane pump (Dolman, 1952).

trifugal type of pump is stopped there is a tendency for the fluid to backflow. Figures 493 and 494 depict some centrifugal pumps.

Other specialized types of pumps are available, but, generally, the pumps used by the petroleum industry fall into the two categories discussed.

Power for driving the various types of pumps is usually derived from electric motors, internal combustion engines, or steam drives. Any one of these sources may be adapted for use with either reciprocating pumps or centrifugal pumps. Most rotary pumps are driven by electric motor.

THE AIR POLLUTION PROBLEM

Operation of various pumps in the handling of fluids in petroleum process units can result in the release of air contaminants. Volatile materials such as hydrocarbons, and odorous substances such as hydrogen sulfide or mercaptans are of particular concern because of the large volumes handled. Both reciprocating and centrifugal pumps can be sources of emissions.

The opening in the cylinder or fluid end through which the connecting rod actuates the piston is the major potential source of contaminants from a reciprocating pump. In centrifugal pumps, normally the only potential source of leakage occurs where the drive shaft passes through the impeller casing.

AIR POLLUTION CONTROL EQUIPMENT

Several means have been devised for sealing the annular clearance between pump shafts and fluid casings to retard leakage. For most refinery applications, packed seals and mechanical seals are widely used.

Packed seals can be used on both positive displacement and centrifugal type pumps (Elonka, 1956). Typical packed seals, as shown in Figure 495, generally consist of a stuffing box filled with sealing material that encases the moving shaft. The stuffing box is fitted with a takeup ring that is made to compress the packing and cause it to tighten around the shaft. Materials used for packing vary with the product temperature, physical and chemical properties, pres-

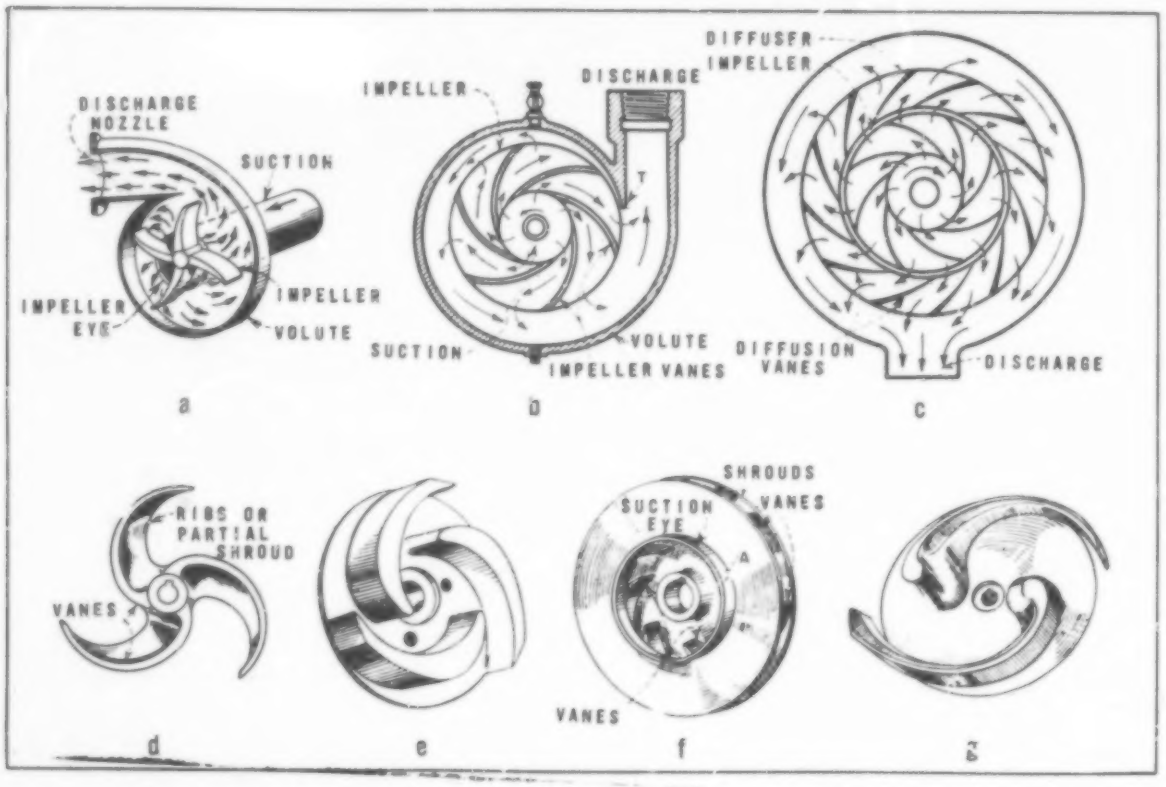


Figure 493. Centrifugal pumps: (a) Principle of centrifugal-type pump, (b) radial section through volute-type pump, (c) radial section through diffuser-type pump, (d) open impeller (e) semi-enclosed impeller, (f) closed impeller, (g) nonclog impeller (Dolman, 1952).

sure, and pump type. Some commonly used materials are metal, rubber, leather, wood, and plastics.

Lubrication of the contact surfaces of the packing and shaft is effected by a controlled amount of product leakage to the atmosphere. This feature makes packing seals undesirable in applications where the product can cause a pollution problem. The packing itself may also be saturated with some material such as graphite or oil that acts as a lubricant. In some cases cooling or quench water is used to cool the impeller shaft and the bearings.

The second commonly used means of sealing is the mechanical seal (Elonka, 1956), which was developed over a period of years as a means of reducing leakage from pump glands. This type of seal can be used only in pumps that have a rotary shaft motion. A simple mechanical seal consists of two rings with wearing surfaces at right angles to the shaft (see Figure 496). One ring is stationary while the other is attached to the shaft and rotates with it. A spring and the action of fluid pressure keep the two faces in contact. Lubrication of the wearing faces is effected by a thin film of the material being pumped The wearing faces are precisely finished to ensure perfectly flat surfaces. Materials used in the manufacture of the sealing rings are many and varied. Choice of materials depends primarily upon properties of fluid being pumped, pressure, temperature, and speed of rotation. The vast majority of rotating faces in commercial use are made of carbon (Woodhouse, 1957).

Emissions to the atmosphere from centrifugal pumps may be controlled in some cases by use of the described mechanical-type seals instead of packing glands. For cases not feasible to control with mechanical seals, specialized types of pumps, such as canned, diaphragm, or electromagnetic, are required.

The canned-type pump is totally enclosed, with its motor built as an integral part of the pump. Seals and attendant leakage are eliminated. The diaphragm pump is another type devoid of seals. A diaphragm is actuated hydraulically, mechanically, or pneumatically to effect a pumping action. The electromagnetic pumps use an electric current passed through the fluid, which is in the presence of a strong magnetic field, to cause motion.

A pressure-seal-type application can reduce packing gland leakage. A liquid, less volatile or dangerous than the product being pumped, is

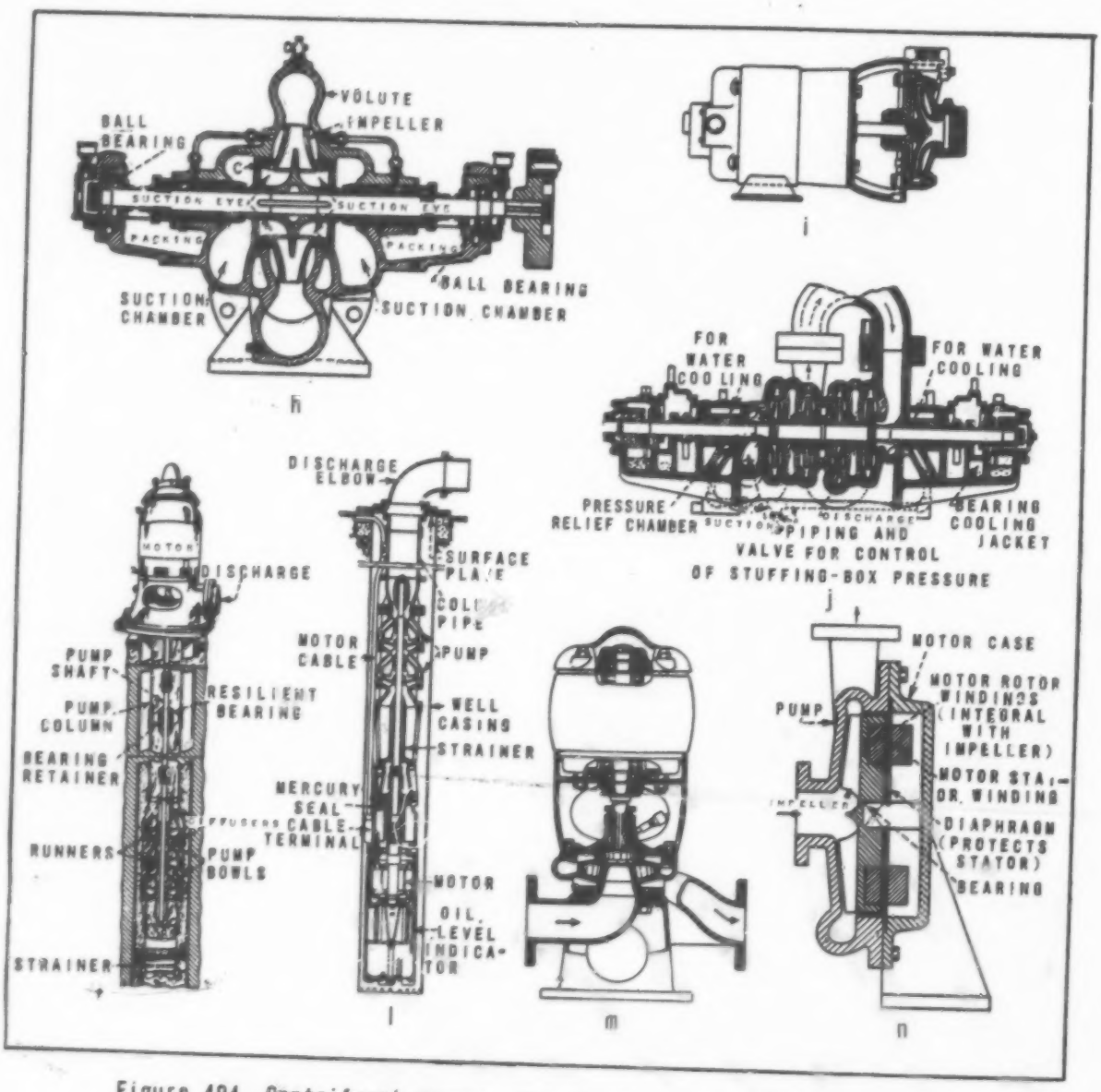


Figure 494. Centrifugal pumps: (h) single-stage, double-suction, split-case, centrifugal pump; (i) close-coupled water pump; (j) four-stage pump with opposed impellers; (k) turbine-type, deep-well pump; (l) submersible-motor, deep-well pump; (m) close-coupled, vertical, turret-type pump; (n) pump with integral motor (Dolman, 1952).

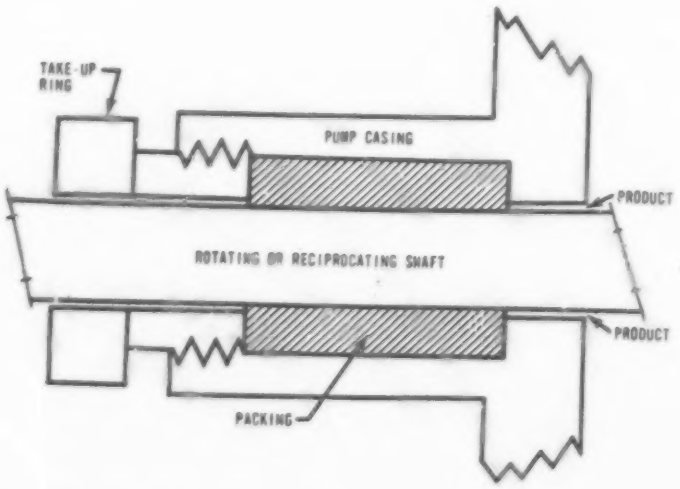


Figure 495. Diagram of simple uncooled packed seal.

introduced between two sets of packing. This sealing liquid must also be compatible with the product. Since this liquid is maintained at a higher pressure than the product, some of it passes by the packing into the product. The pressure differential prevents the product from leaking outward, and the sealing liquid provides the necessary lubricant for the packing gland. Some of the sealing liquid passes the outer packing (hence the necessity of low volatility), and a means should be provided for its disposal.

This application is also adaptable to pumps with mechanical seals. A dual set of mechanical seals similar to the two sets of packing is used.

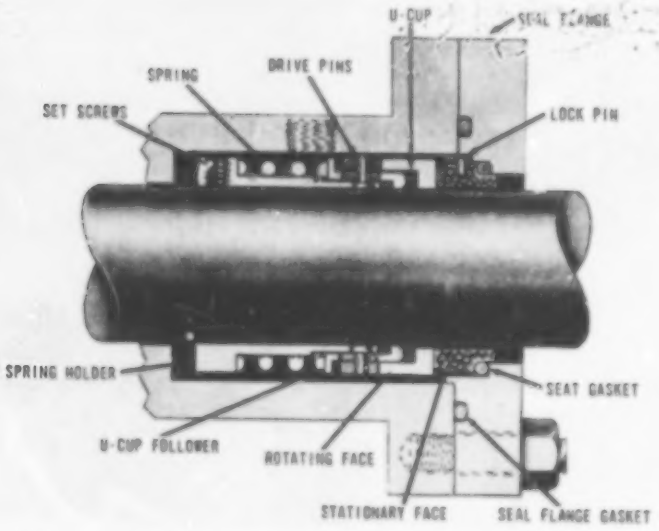


Figure 496. Diagram of simple mechanical seal (Borg-Warner Mechanical Seals. A Division of Borg-Warner Corporation, Vernon, Calif.).

Volatile vapors that leak past a main seal may be vented to vapor recovery by using dual seals and a shaft housing.

Other than the direct methods used to control leakage, operational changes may minimize release of contaminants to the atmosphere. One desirable change is to bleed off pump casings during shutdown to the fuel gas system, vapor recovery facilities, or a flare instead of directly to the atmosphere.

Results of Study to Measure Losses From Pumps

The results of a testing program (Steigerwald, 1958) to establish the magnitude of hydrocarbon losses from pumps are presented in Tables 182 through 185. The data collected during the study are presented in Table 184 as a comparison of the effectiveness of packing glands and mechanical seals in preventing leakage.

Table 182. SCOPE AND RESULTS OF FIELD TESTS ON PUMP SEALS (Steigerwald, 1958)

Group No.[a]	Total number of seals	Seals inspected		Measured leaks		Small leaks		Hydrocarbon loss from inspected pumps, lb/day
		Number	% of total	Number	Hydrocarbon loss, lb/day	Number	Hydrocarbon loss, lb/day[b]	
1	76	14	18	2	60	2	2	62
2	82	13	16	0	0	2	2	2
3	66	12	18	0	0	2	2	2
4	127	21	17	6	294	7	7	301
5	266	59	22	3	19	13	13	32
6	56	16	28	0	0	5	5	5
7	163	34	21	13	262	6	6	268
8	191	35	18	2	23	4	4	27
9	150	19	13	2	7	2	2	9
Subtotal	1,177	223	19	28	665	43	43	708
10	92	15	16	5	26	2	2	28
11	78	9	12	1	4	2	2	6
12	68	9	13	0	0	3	3	3
13	49	0	0	0	0	0	0	0
14	179	21	12	12	83	5	5	88
15	103	18	18	0	0	3	3	3
16	100	15	15	6	280	4	4	284
17	175	26	15	6	226	11	11	237
18	124	25	20	2	16	0	0	16
Subtotal	968	138	14	32	635	30	30	665
19	26	6	23	1	23	3	3	26
20	32	5	16	0	0	0	0	0
21	38	8	21	0	0	3	3	3
22	72	13	18	6	383	3	3	386
23	173	29	17	1	71	7	7	78
24	150	17	11	0	0	0	0	0
25	60	7	12	4	19	2	2	21
26	40	7	18	3	82	3	3	85
27	50	20	40	0	0	1	1	1
Subtotal	641	112	17	15	578	22	22	600
Totals	2,786	473	17	75	1,878	95	95	1,973

[a]Group numbers represent a specific combination of pump type, seal type, pump operation, and product.
[b]A value of 1 pound per day was assigned to a small leak on a pump seal.

Table 183. EXTRAPOLATION OF FIELD DATA BY SAMPLING GROUPS TO OBTAIN A TOTAL LOSS FIGURE (Steigerwald, 1958)

1	2	3	4	5	6
Group No.[a]	Total number of seals	Number of seals inspected	Hydrocarbon loss from inspected seal, lb/day	Avg hydrocarbon loss per inspected seal, lb/day[b]	Total hydrocarbon loss, lb/day[c]
1	76	14	62	4.4	335
2	82	13	2	0.2	16
3	66	12	2	0.2	13
4	127	21	301	14.4	1,830
5	266	59	32	0.6	160
6	56	16	5	0.3	17
7	163	34	268	7.9	1,289
8	191	35	27	0.8	153
9	150	19	9	0.5	75
10	92	15	28	1.8	166
11	78	9	6	0.7	55
12	68	9	3	0.3	20
13	49	0	--	--	--
14	179	21	88	4.2	752
15	103	18	3	0.2	21
16	100	15	284	18.8	1,880
17	175	26	237	9.1	1,592
18	124	25	16	0.6	74
19	26	6	26	4.3	112
20	32	5	0	0	0
21	38	8	3	0.4	15
22	72	13	386	29.6	2,131
23	173	29	78	2.7	467
24	150	17	0	0	0
25	60	7	21	3.0	180
26	40	7	85	12.1	484
27	50	20	1	0.1	5
Totals	2,786	473	1,973	4.2	11,842 or 6 tons per day

[a]Group numbers represent a specific combination of pump type, seal type, pump operation, and product.
[b]Divide hydrocarbon loss from inspected seal, lb/day, by number of seals inspected.
[c]Multiply average hydrocarbon loss per inspected seal, lb/day, by total number of seals.

The slight difference between the average losses from mechanical seals and packed glands during handling of highly volatile hydrocarbons needs further clarification. Pumps in continuous service show an average loss per seal of 18.3 and 7.9 pounds per day for packed and mechanical seals, respectively, indicating that mechanical seals are far more efficient when running continuously. On spare or standby service the packed seals are more effective, losing 1.8 pounds per day to an average loss of 4.4 pounds from mechanical seals. Reciprocating pumps handling light products are the worst offenders both in incidence of leak and magnitude of average emissions. The largest leak encountered in the study, 266 pounds per day, was from a reciprocating pump on intermittent service handling liquefied petroleum gas.

AIRBLOWN ASPHALT

Asphalt is a dark brown to black, solid or semi-solid material found in naturally occurring deposits or as a colloidal suspension in crude oil. Analytical methods have been used to separate asphalt into three component groups--asphaltenes, resins, and oils. A particular grade of asphalt may be characterized by the amounts of each group it contains. The asphaltene particle provides a nucleus about which the resin forms a protective coating. The particles are suspended

Table 184. EFFECTIVENESS OF MECHANICAL AND PACKED SEALS ON VARIOUS TYPES OF HYDROCARBONS (Steigerwald, 1958)

Seal type	Pump type	Type hydrocarbon being pumped, lb Reid	Avg hydrocarbon loss per inspected seal, lb/day	Leak incidence	
				Small leaks,[a] % of total inspected	Large leaks, % of total inspected
Mechanical	Centrifugal	> 26	9.2	19	21
		5 to 26	0.6	18	5
		0.5 to 5	0.3	19	4
Avg		> 0.5	3.2	19	13
Packed	Centrifugal	> 26	10.3	20	37
		5 to 26	5.9	32	34
		0.5 to 5	0.4	12	4
Avg		> 0.5	4.8	22	23
Packed	Reciprocating	26	16.6	31	42
		5 to 26	4.0	24	10
		0.5 to 5	0.1	9	0
Avg		> 0.5	5.4	20	13

[a]Small leaks lose less than 1 pound of hydrocarbon per day.

Table 185. AVERAGE PUMP SEAL LOSSES BY VOLATILITY OF PRODUCT BEING PUMPED (Steigerwald, 1958)

Product, lb Reid	Total number of seals reported	Number of seals inspected	Avg hydrocarbon loss per inspected seal, lb/day
26	765	125	11.1
5 to 26	1,216	204	2.7
0.5 to 5	805	144	0.3

in an oil that is usually paraffinic but can be naphthenic or napthene-aromatic.

RECOVERY OF ASPHALT FROM CRUDE OIL

Over 90 percent of all asphalt used in the United States is recovered from crude oil (Kirk and Othmer, 1947). The method of recovery depends upon the type of crude oil being processed. Practically all types of crudes are first distilled at atmospheric pressure to remove the lower boiling materials such as gasoline, kerosene, diesel oil, and others. Recovery of nondistillable asphalt from selected topped crudes may then be accomplished by vacuum distillation, solvent extraction, or a combination of both.

A typical vacuum distillation unit is depicted in Figure 497. A unit such as this uses a heater, preflash tower, vacuum vessel, and appurtenances for processing topped crudes. Distillation of topped crude under a high vacuum removes oils and wax as distillate products, leaving the asphalt as a residue. The amount of oil distilled from the residue asphalt controls its properties; the more oil and resin or oily constituents removed by distillation, the harder the residual asphalt. Residual asphalt can be used as paving material or it can be further refined by airblowing.

Asphalt is also produced as a secondary product in solvent extraction processes. As shown in Figure 498, this process separates the asphalt from remaining constituents of topped crudes by differences in chemical types and molecular weights rather than boiling points as in vacuum distillation processes. The solvent, usually a light hydrocarbon such as propane or butane, is used to remove selectively a gas-oil fraction from the asphalt residue.

AIRBLOWING OF ASPHALT

Economical removal of the gas-oil fraction from topped crude, leaving an asphaltic product, is occasionally feasible only by airblowing the crude residue at elevated temperatures. Excellent paving-grade asphalts are produced by this method. Another important application of airblowing is in the production of high-quality specialty asphalts for roofing, pipe coating, and similar uses. These asphalts require certain plastic properties imparted by reacting with air.

Airblowing is mainly a dehydrogenation process. Oxygen in the air combines with hydrogen in the oil molecules to form water vapor. The progressive loss of hydrogen results in polymerization or condensation of the asphalt to the desired consistency. Blowing is usually carried out batchwise in horizontal or vertical stills equipped to blanket the charge with steam, but it may also be

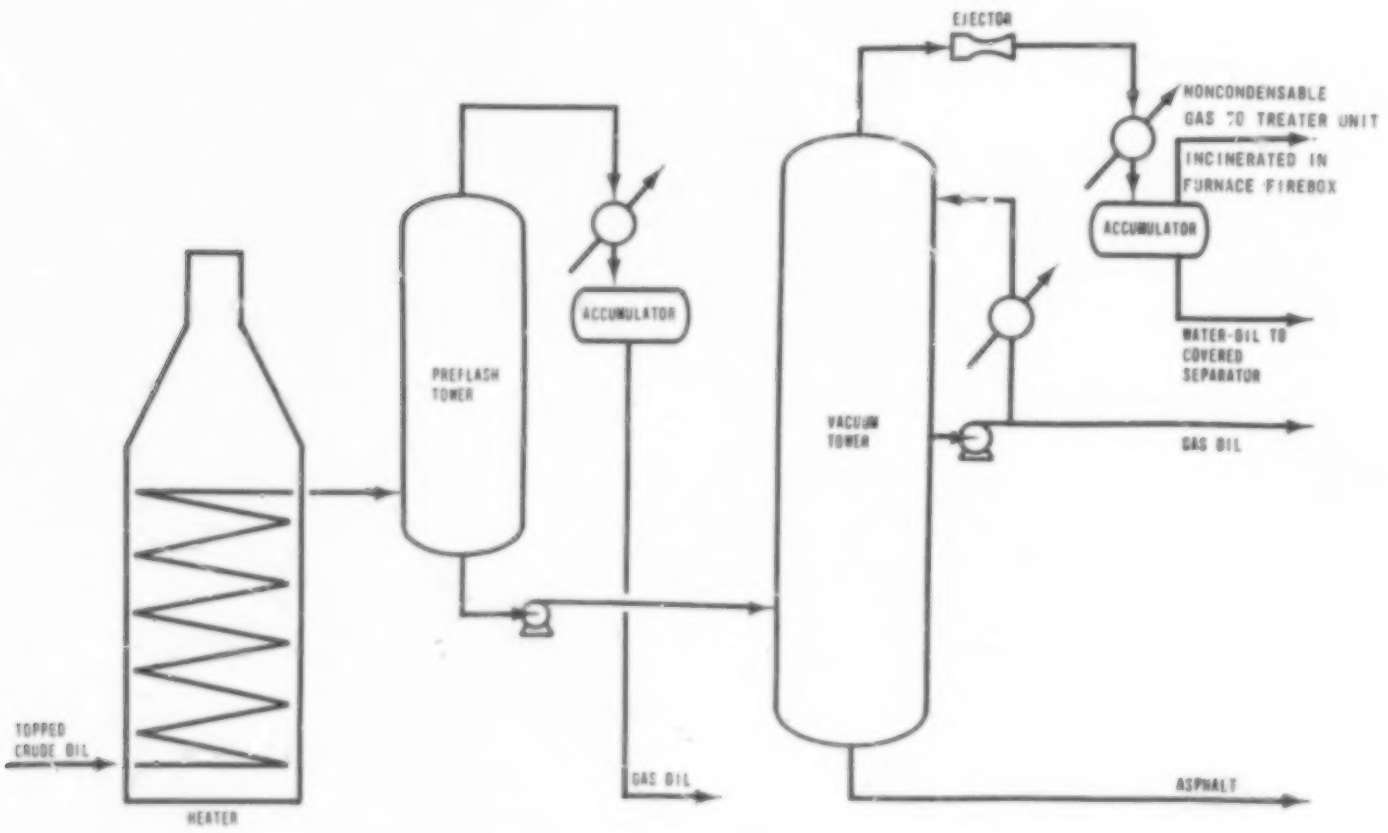


Figure 497. Flow diagram of vacuum distillation unit.

done continuously. Vertical stills are more efficient because of longer air-asphalt contact time. The asphalt is heated by an internal fire-tube heater or by circulating the charge material through a separate tubestill. A temperature of 300° to 400°F is reached before the airblowing cycle begins. Air quantities used range from 5 to 20 cubic feet per minute per ton of charge (Barth, 1958). Little additional heat is then needed since the reaction becomes exothermic. Figure 499 depicts the flow through a typical batch-type unit.

THE AIR POLLUTION PROBLEM

Effluents from the asphalt airblowing stills include oxygen, nitrogen and its compounds, water vapor, sulfur compounds, and hydrocarbons as gases, odors, and aerosols. Discharge of these vapors directly to the atmosphere is objectionable from an air pollution control standpoint. The disagreeable odors and airborne oil particles entrained with the gases result in nuisance complaints. Disposal methods are available that can satisfactorily eliminate the pollution potential of the effluents.

AIR POLLUTION CONTROL EQUIPMENT

Control of effluent vapors from asphalt airblowing stills has been accomplished by scrubbing and incineration, singly or in combination. Most installations use the combination. Potential air pollutants can be removed from asphalt still gases by scrubbing alone. One effective control installation in Los Angeles County uses sea water for one-pass scrubbing of effluent gases from four asphalt airblowing stills. The fume scrubber is a standard venturi-type unit. The scrubber effluent is discharged into an enclosed oil-water gravity-type separator for recovery of oil, which is reprocessed or used as fuel. Effluent gases from the covered separator that collects the scrubber discharge are not incinerated but flow through a steam-blanketed stack to the atmosphere. The system, shown in Figure 500, removes essentially all potential air pollutants from the effluent stream. A limiting factor in the application of this method of control is the water supply. Since a high water-to-vapor scrubbing ratio (100 gallons/1,000 scf) is necessary, an economical source of water should be readily available to supply the large volume required for one-pass operation.

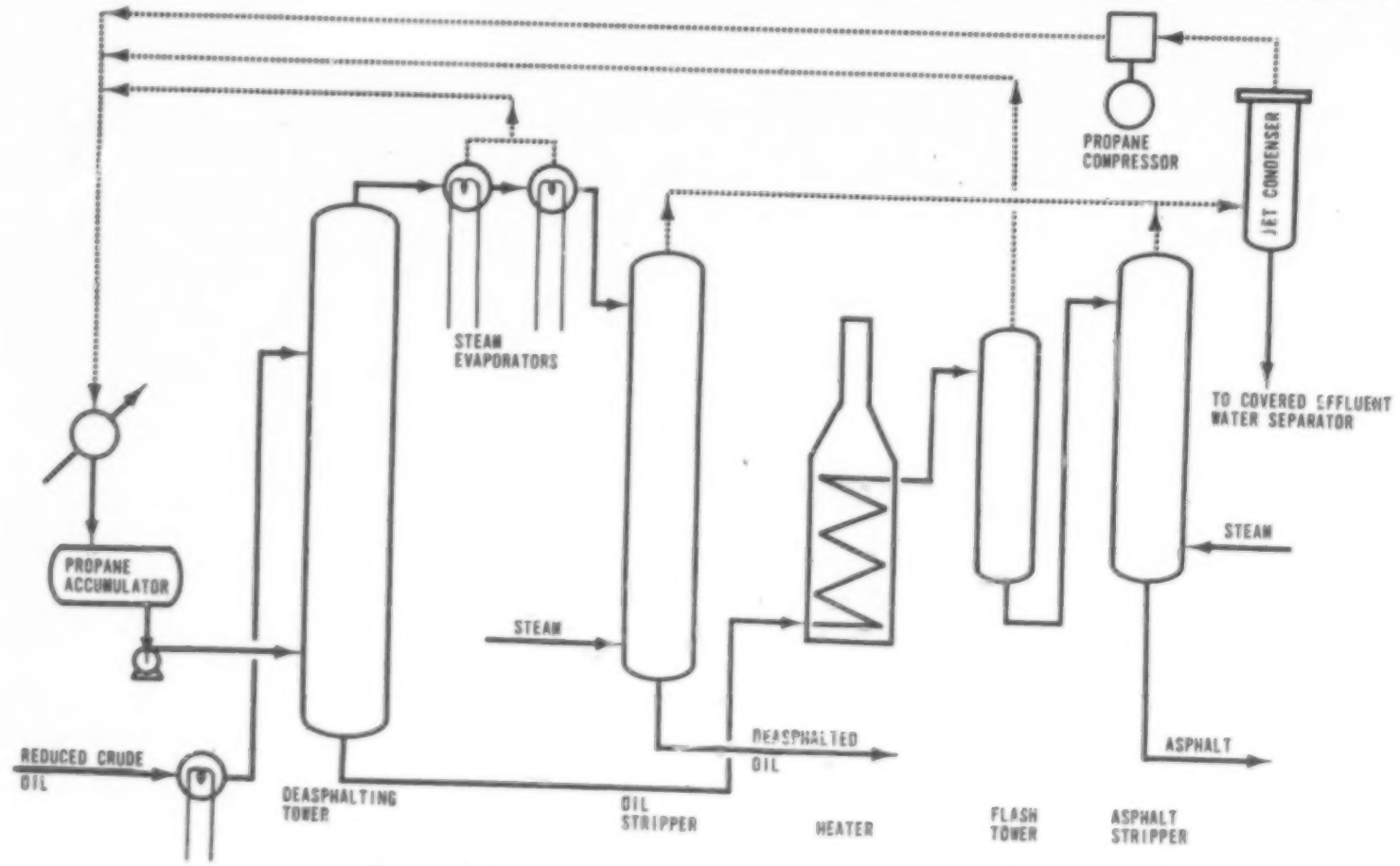


Figure 498. Flow diagram of propane deasphalting unit.

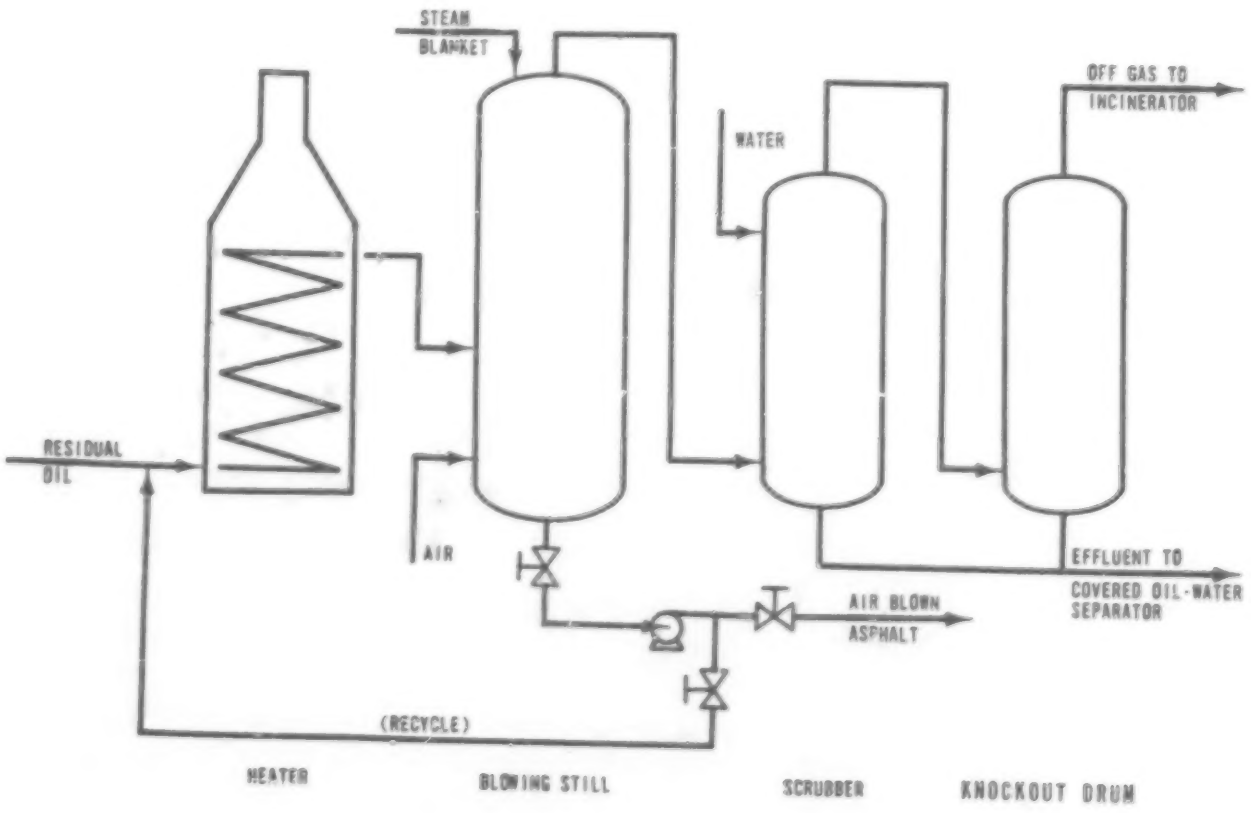


Figure 499. Flow diagram of airblown asphalt manufacture (batch process).

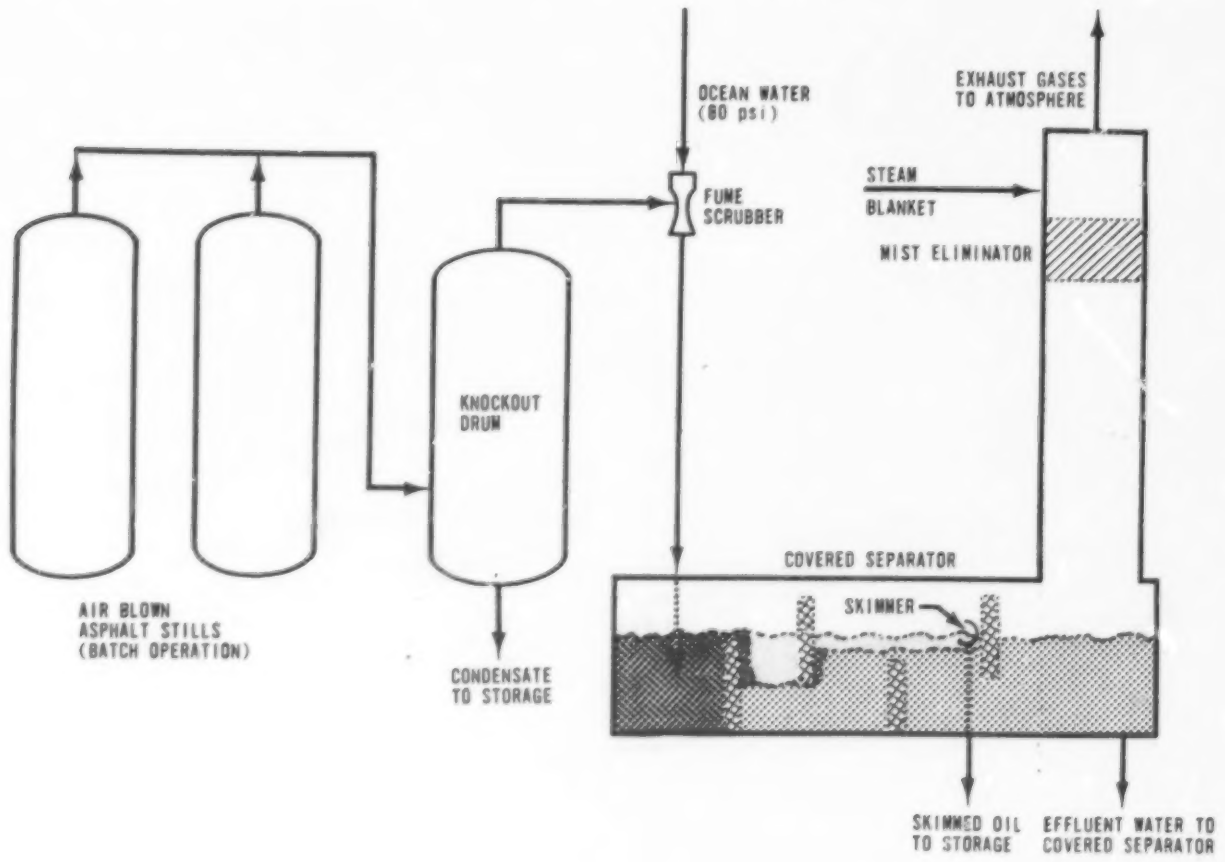


Figure 500. Flow diagram of scrubbing system.

Where removal of most of the potential air pollutants is not feasible by scrubbing alone, the noncondensables must be incinerated. Essential to effective incineration is direct-flame contact with the vapors, a minimum retention time of 0.3 second in the combustion zone, and maintenance of a minimum combustion chamber temperature of 1,200°F. Other desirable features include turbulent mixing of vapors in the combustion chamber, tangential flame entry, and adequate instrumentation. Primary condensation of any steam or water vapor allows use of smaller incinerators and results in fuel savings. Some of the heat released by incineration of the waste gases may be recovered and used for generation of steam. General design features of waste gas afterburners and boilers are discussed elsewhere in this manual.

Catalytic fume burners are not recommended for the disposal of vapors from the airblowing of asphalt because the matter entrained in the vapors would quickly clog the catalyst bed.

VALVES

TYPES OF VALVES

Valves are employed in every phase of the petroleum industry where petroleum or petroleum product is transferred by piping from one point to another. There is a great variety of valve designs, but, generally, valves may be classified by their application as flow control or pressure relief.

Manual and Automatic Flow Control Valves

Manual and automatic flow control valves are used to regulate the flow of fluids through a system. Included under this classification are the gate, globe, angle, plug, and other common types of valves. These valves are subject to product leakage from the valve stem as a result of the action of vibration, heat, pressure, corrosion, or improper maintenance of valve stem packing (see Figure 501).

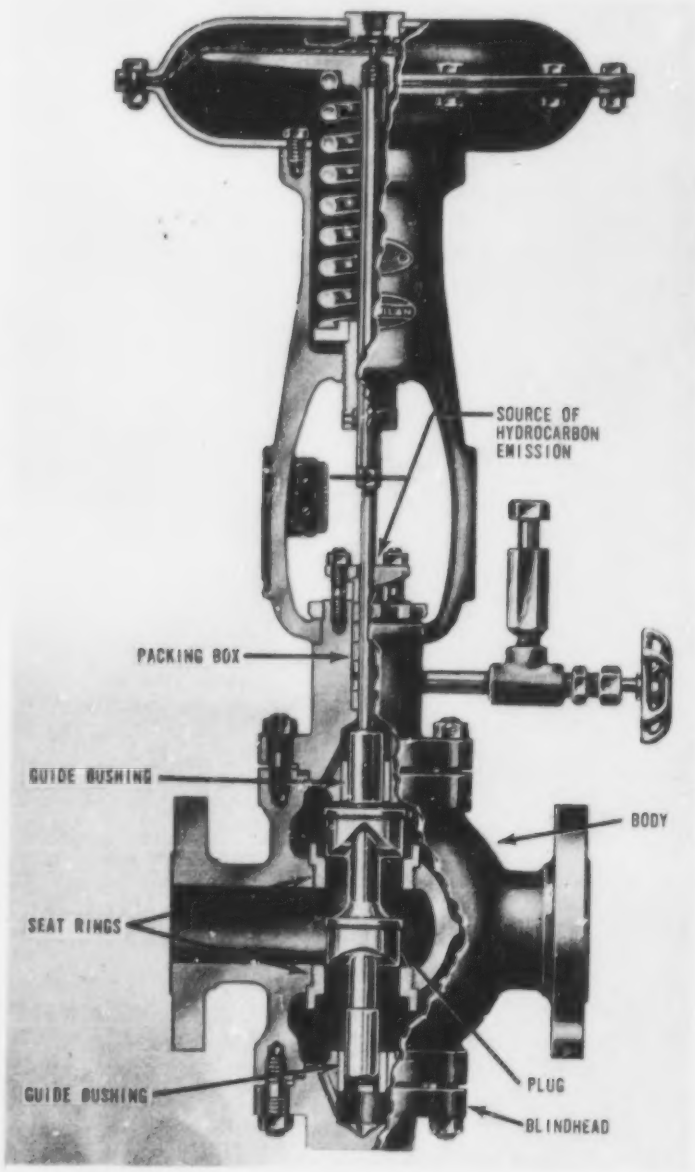


Figure 501. Typical valve showing various parts and potential source of hydrocarbon emission from the valve stem (Mason-Neilan, Division of Worthington Corporation, Norwood, Mass.).

Pressure Relief and Safety Valves

Pressure relief and safety valves are used to prevent excessive pressures from developing in process vessels and lines. The relief valve designates liquid flow while the safety valve designates vapor or gas flow. These valves may develop leaks because of the corrosive action of the product or because of failure of the valve to reseat properly after blowoff. Rupture discs are sometimes used in place of pressure relief valves. Their use is restricted to equipment in batch-type processes. The maintenance and operational difficulties caused by the inaccessibility of many pressure relief valves may allow leakage to become substantial.

THE AIR POLLUTION PROBLEM

Quantitative data as to actual extent of emissions to the atmosphere from this leakage are somewhat limited, but available data indicate that emissions vary over a wide range. Liquid leakage results in emissions from evaporation of liquid while gas leakage results in immediate emissions. The results of a test program (Kanter et al., 1958) conducted to establish the magnitude of hydrocarbon emissions from valves are presented in Table 186. In this program, valves in a group of 11 Los Angeles County refineries were surveyed. Both liquid and gaseous leaks were measured or estimated in the survey. Leaks were detected by visible means for liquid leaks, and by spraying with soap solution followed by inspection for bubble formation for gaseous leaks. Liquid leakage rates were measured by collecting liquid over a period of time. Flow rates for gaseous leaks were determined by enclosing the valve in polyethylene bags and venting the vapor through a wet test meter.

Apparent from Table 186 is that 70 percent of the measurable leaks in gas service average less than 9.1 pounds of emissions per day. In liquid service, 90 percent of the measurable leaks average less than 8.8 pounds of emissions per day. Consideration of remaining data shows that the frequency distribution of leaks is extremely skewed.

An example of low leakage rate was observed in one refinery where over 3,500 valves handling a wide variety of products under all conditions of temperature and pressure were inspected. The average leak rate was 0.038 pound per day per valve.

Examples of high leakage rates were found in two refineries where all 440 valves inspected in gas service had an average leak rate of 1.6 pounds per day per valve, and in one other refinery where all 1,335 valves inspected in liquid service had an average leak rate of 0.32 pound per day per valve.

These examples illustrate the wide divergence from the average valve leak rate that can exist among refineries in a single area, all subject to the same obligations to restrict their emissions to the greatest possible extent. These results could not be applied, even approximately, to refineries in other areas where standards may be different.

These testing programs were also conducted on pressure relief valves in the same oil refineries. The results of this phase of the program are shown in Table 187. As can be seen from the data, relief valves on operational units have a slightly lower leak incidence but a much higher average

Table 186. LEAKAGE OF HYDROCARBONS FROM VALVES OF REFINERIES IN LOS ANGELES COUNTY (Kanter et al., 1958)

	Valves in gaseous service	Valves in liquid service	All valves
Total number of valves	31,000	101,000	132,000
Number of valves inspected	2,258	7,263	9,521
Small leaks[a]	256	768	1,024
Large leaks	118	79	197
Leaks measured	24	76	100
Total measured leakage, lb/day	218	670	888
Average leak rate--large leaks, lb/day	9.1	8.8	8.9
Total from all large leaks, lb/day	1,072	708	1,780
Estimated total from small leaks, lb/day[b]	26	77	103
Total estimated leakage from all inspected valves, lb/day	1,098	785	1,883
Average leakage per inspected valve, lb/day	0.486	0.108	0.198

[a]Small leaks are defined as leaks too small to be measured--those estimated to be less than 0.2 pound per day.
[b]Leaks too small to be measured were estimated to have an average rate of 0.1 pound per day. This is one-half the smallest measured rate.

leakage rate than valves on pressure storage vessels do. Moreover, dual-type valves (two single relief valves connected in parallel to ensure effective release of abnormal pressures) on pressure storage vessels have a greater leak incidence and a larger average leakage rate than single-type valves on similar service do. For valves on operational vessels, the average for all refineries was 2.9 pounds of hydrocarbons per day per valve. Average losses from specific refineries, however, varied from 0 to 9.1 pounds per day per valve. Under diverse conditions of operation and maintenance, emissions can vary greatly from one refinery to another.

Table 187. LEAKAGE OF HYDROCARBONS FROM PRESSURE RELIEF AND SAFETY VALVES OF REFINERIES IN LOS ANGELES COUNTY (Kanter et al., 1958)

Valve group	Number of valves reported	Number of valves tested	Hydrocarbon emission, lb/day	Emission per tested valve, lb/day[a]	Total emission, lb/day
Operational units	1,113	165	480	2.90	3,230
Pressure storage:					
Single	237	174	56	0.32	80
Dual	115	79	98	1.24	140

[a]Divide hydrocarbon emissions, lb/day, by number of valves tested.
[b]Multiply number of valves reported by emission per tested valve, lb/day.

Total Emissions From Valves

Since emissions to the atmosphere from valves are highly dependent upon maintenance, total valve losses cannot be estimated accurately. From the testing program mentioned, emissions from valves averaged 12 percent of the total emissions from all refineries in Los Angeles County. As of 1963, hydrocarbon emissions from valves in Los Angeles County refineries are estimated at about 11 tons per day. As stated previously, however, these emissions varied greatly from one refinery to another, and average percentage figures should not be used in predicting emissions from a given refinery.

AIR POLLUTION CONTROL EQUIPMENT

Obviously, the controlling factor in preventing leakage from valves is maintenance. An effective schedule of inspection and preventive maintenance can keep leakage at a minimum. Minor leaks that might not be detected by casual observation can be located and eliminated by thorough periodic inspections. New blind designs are being incorporated in refinery pipeline systems in conjunction with flow valves (see Figure 502). This is done to ensure against normal leakage that can occur through a closed valve.

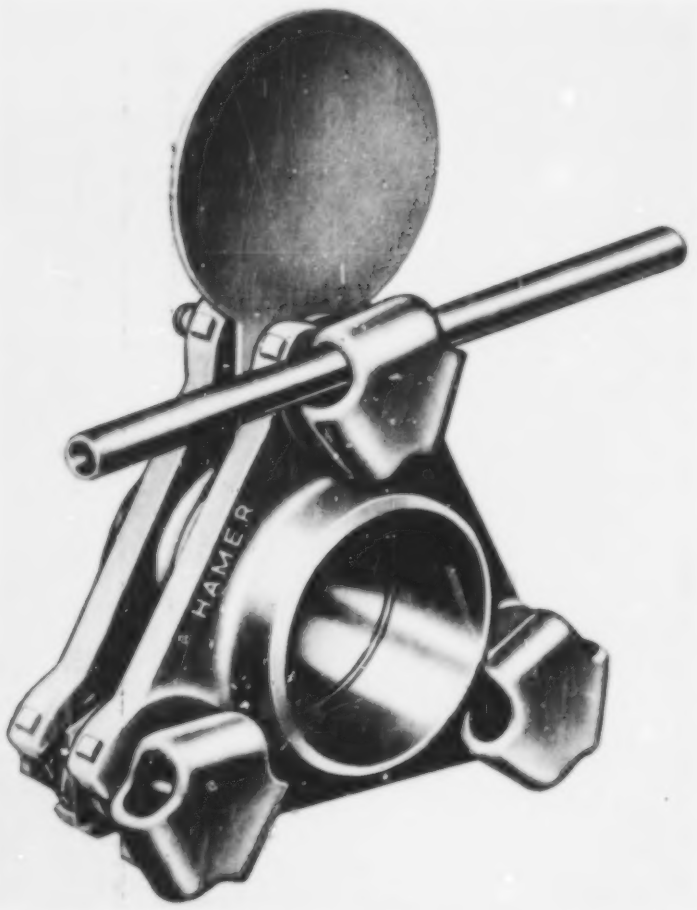


Figure 502. Bar-operated line blind that is ideal for installation ahead of shutoff valve to ensure against valve leaks and vapor emissions from valve stem (Hamer Oil Tool Co. Catalog Sheet., Long Beach, Calif.).

Emissions from pressure relief valves are sometimes controlled by manifolding to a vapor control device, such as described in Chapter 5. Normally, these disposal systems are not designed exclusively to collect vapors from relief valves. The primary function of the system may be to collect off gases produced by a process unit, or vapors released from storage facilities, or those released by depressurizing equipment during shutdowns.

Another method of control to prevent excessive emissions from relief valve leakage is the use of a dual valve with a shutoff interlock. A means of removing and repairing a detected leaking valve without waiting until the equipment can be taken out of service is thus provided. The practice of allowing a valve with a minor leak to continue in service without correction until the operating unit is shut down for general inspection is common in many refineries. This practice should be kept at a minimum.

A rupture disc is sometimes used to protect against relief valve leakage caused by excessive corrosion. The disc is installed on the pressure side of the relief valve. The space between the rupture disc and relief valve seat should be protected from pinhole leaks that could occur in the rupture disc. Otherwise, an incorrect pressure differential could keep the rupture disc from breaking at its specified pressure. This, in turn, could keep the relief valve from opening, and excessive pressures could occur in the operating equipment.

One method of ensuring against these small leaks in rupture discs is to install a pressure gage and a small manually operated purge valve in the system. The pressure gage would easily detect any pressure increases from even small leaks. In the event of leaks, the vessel would be removed from service, and the faulty rupture disc would then be replaced. A second, but less satisfactory method from an air pollution control standpoint, is to maintain the space at atmospheric pressure by installing a small vent opening. Any minute leaks would then be vented directly to the atmosphere, and a pressure increase could not exist.

COOLING TOWERS

Cooling towers are major items of heat-transfer equipment in the petroleum and petrochemical industries. They are designed to cool, by air, the water used to cool industrial processes. Cooling of the water by air involves evaporation of a portion of the water into the air so that the remaining water is cooled by furnishing heat for this evaporation process. This cooled water is used, in turn, in heat-exchange equipment to cool other liquids and gases.

There are two styles of cooling towers--classified by means of air movement. In one style, the earliest developed, the prevailing wind is used for the required ventilation. It has become known as the natural draft or atmospheric type of cooling tower (see Figure 503).

The other type of cooling tower employs fans to move the air and is known as a mechanical-draft cooling tower (see Figure 504). Fan location is used in further classifying the tower as a forced- or induced-draft cooling tower. The forced-draft cooling tower has not proved very satisfactory, since it has a tendency to recirculate its hot, humid exhaust vapor in place of fresh air, and its air distribution is poor because of the 90-degree turn the air must make at high velocity (Kern, 1950).

Spray ponds, once used extensively for cooling of water, have been abandoned in favor of cooling towers. Spray ponds are limited in their performance and suffer from high water losses.

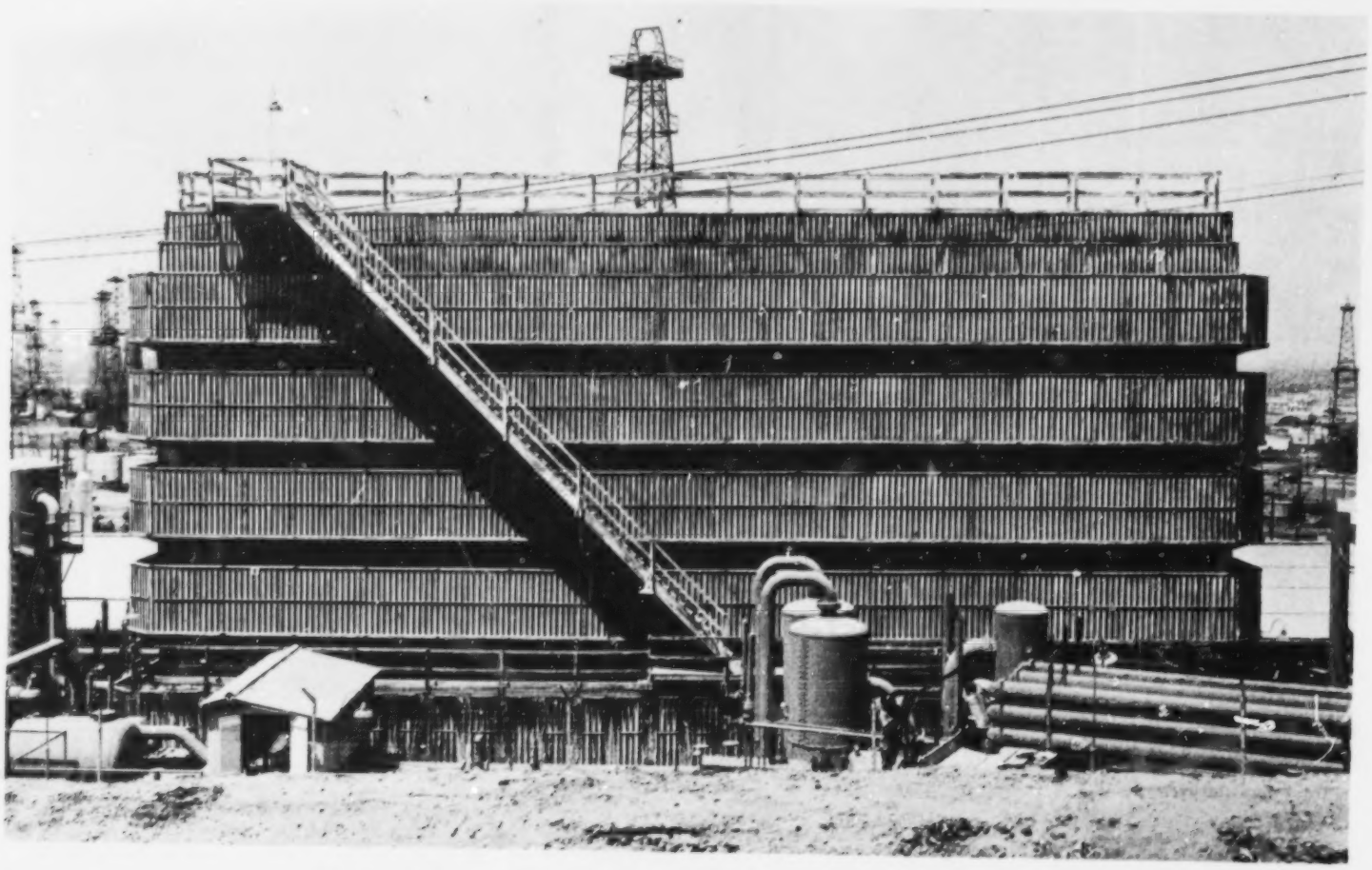


Figure 503. Natural-draft cooling tower (Shell Oil Company, Los Angeles, Calif.).

CHARACTERISTICS OF COOLING TOWER OPERATION

Petroleum and petrochemical operations require large quantities of water for temperature control purposes. The water is normally circulated by pump between the heat-exchange equipment and the cooling tower. The hydrocarbon stream to be cooled can also be circulated directly through the cooling tower. Approximately 1,000 Btu is required to evaporate 1 pound of water. This is equivalent to cooling 100 pounds of water 10°F. Thus, 1 percent of water is lost through evaporation for every 10 degrees of cooling accomplished. Additionally, a spray loss amounting to no more than 0.2 percent must be included for properly designed atmospheric or mechanical-draft towers. Water cannot be cooled below the wet bulb temperature of the air entering the cooling tower.

The performance of an individual cooling tower is governed by the ratio of weights of air to water and the time of contact between the air and water. Commercially, the variation in the ratio of air to water is first obtained by maintaining the air velocity constant at approximately 350 fpm per square foot of active tower area and by varying the water concentration (Perry, 1950). A secondary operation calls for varying the air velocity to meet the cooling requirements. The contact time between water and air is a function of the time required for the water to be discharged from distribution nozzles and fall through a series of gridded decks to the tower basin. Thus, the contact time is governed by the tower height. If the contact time is insufficient, the ratio of air to water cannot be increased to obtain the required cooling. A minimum cooling tower height must be maintained. Where a wide approach (difference between the cold water temperature and the wet bulb temperature of the inlet air) of 15° to 20°F to the wet bulb temperature, and a 25° to 35°F cooling range (difference between the temperature of the hot and cold water) are required, a relatively low cooling tower is adequate (15 to 20 feet). Other ranges are shown in Table 188.

The cooling performance of a tower with a set depth of packing varies with water concentration. Maximum contact and performance have been found with a water concentration of 2 to 3 gallons of water per minute per square foot of ground area. The problem in designing a cooling tower is one of determining the proper concentration

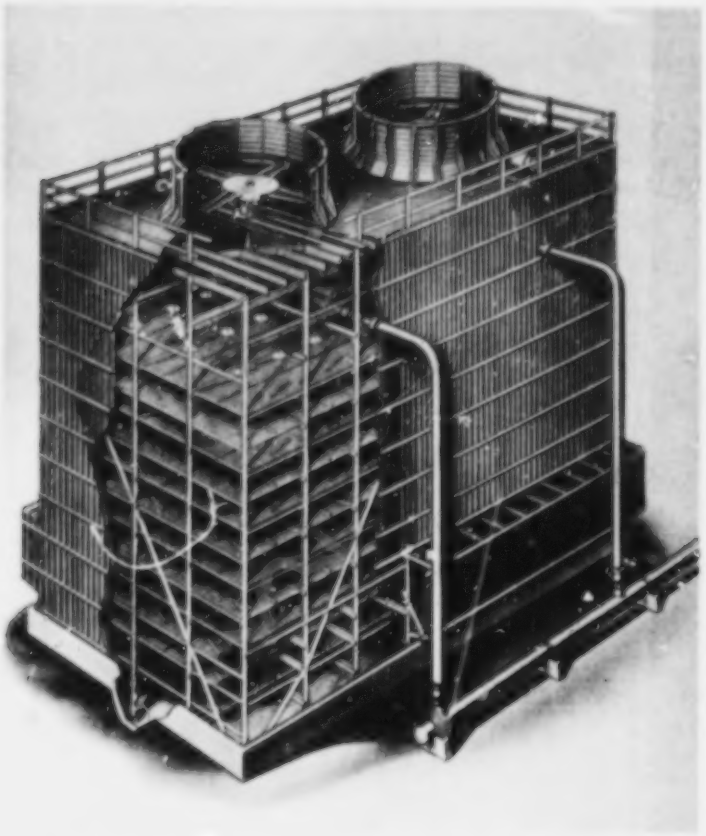


Figure 504. Cutaway view of a mechanical-draft cooling tower (Fluor Products Company, Inc., Santa Rosa, Calif.).

of water to obtain desired cooling. A high cooling tower must be used if the water concentration is less than 1.6 gallons per square foot. Low towers can be employed if the water concentration exceeds 3 gallons per square foot. If the required water concentration is known, the tower area can be found by dividing the water circulation rate (gallons per minute) by the water concentration (gallons per minute per square foot).

The required tower size (Perry, 1950) is thereby dependent upon: (1) cooling range (hot water minus cold water temperature); (2) approach (cold water minus wet bulb temperature); (3) amount of liquid to be cooled; (4) wet bulb temperature; (5) air velocity through cell; and (6) tower height.

Various technical articles are available by which a cooling tower may be designed for a specific duty (Natural Gas Processors Suppliers Association, 1957; Perry, 1950).

THE AIR POLLUTION PROBLEM

Cooling towers used in conjunction with equipment processing hydrocarbons and their derivatives are potential sources of air pollution because of possible contamination of the water. The cooling water may be contaminated by leaks from the process side of heat-exchange equipment, direct and intentional contact with process streams, or improper process unit operation. As this water is passed over a cooling tower, volatile hydrocarbons and other materials accumulated in the water readily evaporate into the atmosphere. When odorous materials are contained in the water, a nuisance is easily created.

Table 188. COOLING TOWER APPROACH VERSUS WATER TRAVEL

Approach, °F	Cooling range, °F	Water travel, ft
15 to 20	25 to 35	15 to 20
8 to 15	25 to 35	25 to 30
4 to 8	25 to 35	35 to 40
4[a]	-	35 to 40

[a]Designing cooling towers with an approach of less than 4°F is not economical.

Inhibitors or additives used in the cooling tower to combat corrosion or algae growth should not cause any significant air pollution emissions, nor should the water-softening facilities common to many cooling towers be a problem.

A survey (Bonamassa and Yee, 1957) of the oil refineries operating in Los Angeles County indicated hydrocarbon concentrations of approximately 20 percent in the cooling water of the cooling towers (see Table 189). Cooling towers in which hydrocarbons were detected were tested quantitatively. Three tons of hydrocarbons per day were found being discharged into the atmosphere from these sources. Individually the emissions varied from 4 to 1,500 pounds per cooling

Table 189. HYDROCARBON EMISSIONS FROM COOLING TOWERS (Bonamassa and Yee, 1957)

Cooling tower	Water circulation, gpm	Hydrocarbon emissions, lb/day (as hexane)
1	14,000	1,570
2	3,120	1,400
3	28,000	700
4	3,000	616
5	1,000	532
6	14,000	318
7	14,000	289
8	12,000	239
9	18,000	186
10	1,000	147
11	15,000	129
12	10,000	56
13	8,000	22
14	1,800	10
15	700	10
16	1,000	8
17	400	4
		Total 6,236

tower per day. A study of operating variables failed to indicate any correlation among the emissions, the size of the tower, the water circulation rate, or the particular duty of the tower. Apparently the amount of hydrocarbon present in the water depends upon the state of maintenance of the process equipment, particularly the heat-exchange equipment, condensers, and coolers through which the water is circulated. The quantity and type of emissions should be determined by observing and testing each tower individually.

One survey of the cooling towers in a designated area is felt to be representative of the emissions under existing operating conditions and maintenance practices. The actual emission rate of any specific tower and the degree of odor nuisance vary as leaks develop, are detected, and repaired. Overall leakage probably remains constant in view of the large number of potential sources that can cause new leaks even as the old ones are repaired.

AIR POLLUTION CONTROL EQUIPMENT

The control of hydrocarbon discharges or of release of odoriferous compounds at the cooling tower is not practical. Instead, the control must be at the point where the contaminant enters the cooling water. Hence, systems of detection of contamination in water, proper maintenance, speedy repair of leakage from process equipment and piping, and good housekeeping programs in general are necessary to minimize the air pollution occurring at the cooling tower. Water that has been used in contact with process streams, as in direct-contact or barometric-type condensers, should be eliminated from the cooling tower if this air pollution source is to be completely controlled. Greater use of fin-fan coolers can also control the emissions indirectly by reducing or eliminating the volume of cooling water to be aerated in a cooling tower.

MISCELLANEOUS SOURCES

A number of relatively minor sources of air pollution contribute approximately 10 percent of the total hydrocarbon emissions to the atmosphere from refineries (Kanter et al., 1958). Six of these sources, not discussed elsewhere in this manual, include airblowing, blind changing, equipment turnaround, tank cleaning, use of vacuum jets, and use of compressor engine exhausts.

AIRBLOWING

In certain refining operations, air is blown through heavier petroleum fractions (see Figure 505) for the purpose of removing moisture or agitating the product. The exhaust air is saturated with hydrocarbon vapors or aerosols, and, if discharged directly to the atmosphere, is a source of air pollution. The extent of airblowing operations and the magnitude of emissions from the equipment vary widely among refineries. Results of a survey (Kanter et al., 1958) on the magnitude of hydrocarbon emissions from airblowing of petroleum fractions in Los Angeles County refineries, presented in Table 190, show emissions of less than 1/2 ton per day. These refineries operated a total of seven airblowing units with a combined capacity of 25,000 barrels per day and a total airflow rate of 3,300 cfm. The tabulated results do not include airblowing of asphalt, which has been discussed elsewhere in this chapter. Emissions from airblowing for removal of moisture, or for agitation of products may be minimized by replacing the airblowing equipment with mechanical agitators and incinerating the exhaust vapors.

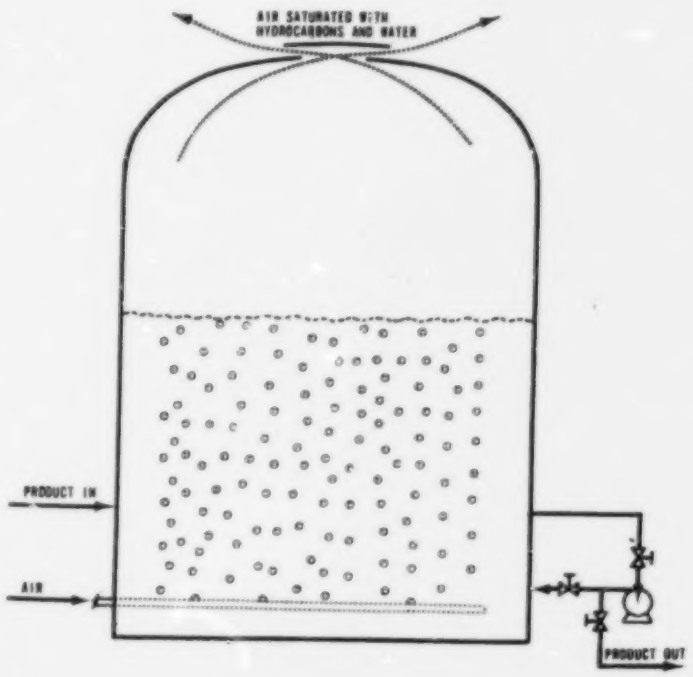


Figure 505. Improvement of product color by means of air agitation, a source of air pollution.

BLIND CHANGING

Refinery operations frequently require that a pipeline be used for more than one product. To prevent leakage and contamination of a particular product, other product-connecting and product-feeding lines are customarily "blinded off." "Blinding a line" is the term commonly used for the inserting of a flat, solid plate between two flanges

of a pipe connection. Blinds are normally used instead of valves to isolate pipelines because a more positive shutoff can be secured and because of generally lower costs. In opening, or breaking, the flanged connection to insert the blind, spillage of product in that portion of the pipeline can occur. The magnitude of emissions to the atmosphere from this spillage is a function of the vapor pressure of the product, type of ground surface beneath the blind, distance to the nearest drain, and amount of liquid holdup in the pipeline.

Table 190. HYDROCARBON EMISSIONS FROM AIRBLOWING OPERATIONS OF REFINERIES IN LOS ANGELES COUNTY (Kanter et al., 1958)

Number of units	Emissions, lb/day
Refinery A (one unit)	905
Refinery B (five units)	35
Refinery C (one unit)	2
Total	942

Results of a survey (Kanter et al., 1958) conducted to evaluate the emissions from blind changing in Los Angeles County refineries indicated that a wide variation exists in the number of pipeline service and corresponding blind changes and in the amount of spillage for different refineries of comparable size. The average emission from blind changing in Los Angeles County refineries was calculated at 0.1 ton per day.

Emissions to the atmosphere from the changing of blinds can be minimized by pumping out the pipeline and then flushing the line with water before breaking the flange. In the case of highly volatile hydrocarbons, a slight vacuum may be maintained in the line. Spillage resulting from blind changing can also be minimized by use of "line" blinds in place of the common "slip" blinds. Line blinds, depicted in Figure 506, do not require a complete break of the flange connection during the changing operation. These blinds use a gear mechanism to release the spectacle plate without actually breaking the line. Combinations of this device in conjunction with gate valves are available to allow changing of the line blind while the line is under pressure from either direction. The line blind is finding many applications in new process equipment where frequent changes in services of pipelines occur. Data compiled during the survey (Kanter et al., 1958) indicate that slip blinds spilled an average of 5 gallons per change compared with line blind valves, which spilled an average of 2 gallons per change.

EQUIPMENT TURNAROUNDS

Periodic maintenance and repair of process equipment are essential to refinery operations. A major phase of the maintenance program is the shutting down and starting up of the various units, usually called a turnaround.

The procedure for shutting down a unit varies from refinery to refinery and between units in a refinery. In general, shutdowns are effected by first shutting off the heat supply to the unit and circulating the feed stock through the unit

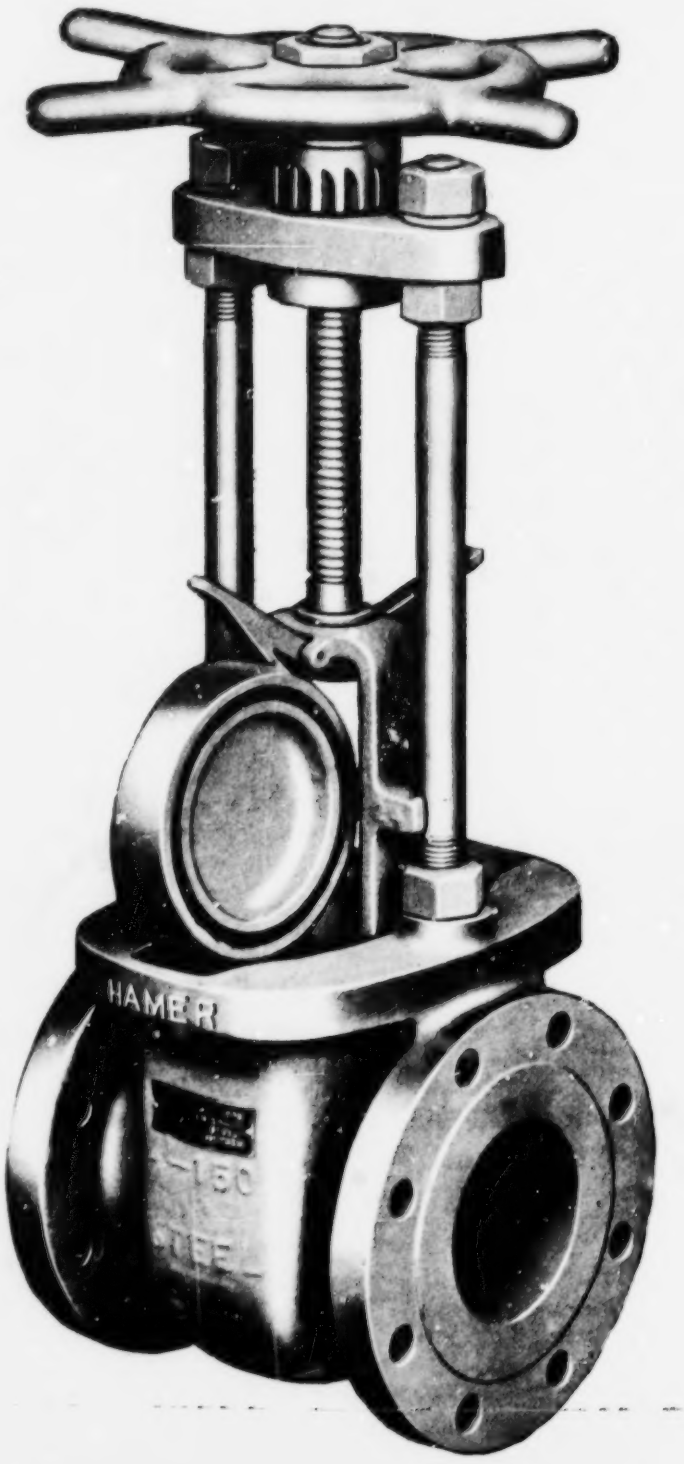


Figure 506. Typical line blind valve (Hamer Oil Tool Company, Long Beach, Calif.).

as it cools. Gas oil may be blended into the feedstock to prevent its solidification as the temperature drops. The cooled liquid is then pumped out to storage facilities, leaving hydrocarbon vapors in the unit. The pressure of the hydrocarbon vapors in the unit is reduced by evacuating the various items of equipment to a disposal facility such as a fuel gas system, a vapor recovery system, a flare, or in some cases, to the atmosphere. Discharging vapors to the atmosphere is undesirable from the standpoint of air pollution control since as much as several thousand pounds of hydrocarbons or other objectionable vapors or odors can be released during a shutdown. The residual hydrocarbons remaining in the unit after depressuring are purged out with steam, nitrogen, or water. Any purged gases should be discharged to the aforementioned disposal facilities. Condensed steam and water effluent that may be contaminated with hydrocarbons or malodorous compounds during purging should be handled by closed water-treating systems.

Results of a survey (Kanter et al., 1958) to determine the magnitude of hydrocarbon emissions from turnarounds in Los Angeles County refineries showed emissions totaling a maximum of 254 tons per year or 0.7 ton per day. Sixty percent of all shutdowns were found to occur on Sunday and Monday. On this basis, the 2-day emissions totaled 3 tons or 152 tons per year.

TANK CLEANING

Storage tanks in a refinery require periodic cleaning and repair. For this purpose, the contents of a tank are removed and residual vapors are purged until the tank is considered safe for entry by maintenance crews. Purging can result in the release of hydrocarbon or odorous material in the form of vapors to the atmosphere. These vapors should be discharged to a vapor recovery system or flare.

Data obtained from the refinery survey (Kanter et al., 1958) were used to estimate the quantity of hydrocarbon emissions to the atmosphere from tank cleaning as follows:

1. When the vapors in the tank were released to a recovery or disposal system before the tank was opened for maintenance, the emissions were considered negligible.

2. When the stored liquid was transferred to another tank, and the emptied vessel was opened for maintenance without purging to a recovery or disposal system, the emission to the atmosphere was considered to be equal to the weight of hydrocarbon vapor occupying the total volume of the tank at the reported pressure. (For floating-roof tanks, the minimum volume was used.)

3. For vapor storage, when tanks were not purged to a recovery or disposal system, estimates were made as described in item 2.

The calculated emissions, for an average of 174 tanks cleaned per year, were 1.3 tons of hydrocarbons per day.

Steam cleaning of railroad tank cars used for transporting petroleum products can similarly be a source of emissions if the injected steam and entrained hydrocarbons are vented directly to the atmosphere. Although no quantitative data are available to determine the magnitude of these emissions, the main objection to this type of operation is its nuisance-causing potential. Some measure of control of these emissions may be effected by condensing the effluent steam and vapors. The condensate can then be separated into hydrocarbon and water phases for recovery. Noncondensable vapors should be incinerated.

USE OF VACUUM JETS

Certain refinery processes are conducted under vacuum conditions. The most practical way to create and maintain the necessary vacuum is to use steam-actuated vacuum jets, singly or in series (see Figure 507). Barometric condensers are often used after each vacuum jet to remove steam and condensable hydrocarbons.

The effluent stream from the last stage of the vacuum jet system should be controlled by condensing as much of the effluent as is practical and incinerating the noncondensables in an afterburner or heater firebox. Condensate should be handled by a closed treating system for recovery of hydrocarbons. The hot well that receives water from the barometric condensers may also have to be enclosed and any off gases incinerated.

USE OF COMPRESSOR ENGINE EXHAUSTS

Refining operations require the use of various types of gas compressors. These machines are often driven by internal combustion engines that exhaust air contaminants to the atmosphere. Although these engines are normally fired with natural gas and operate at essentially constant loads, some unburned fuel passes through the engine. Oxides of nitrogen are also found in the exhaust gases as a result of nitrogen fixation in the combustion cylinders.

Results of a survey (Kanter et al., 1958) conducted to determine the contribution made by compressor engine exhausts to overall emis-

sions from refineries are presented in Table 191. The composition of the hydrocarbons shown was generally over 90 percent methane.

In addition to the compounds listed in the table, aldehydes and ammonia may also be present in engine exhausts. Test data on these components were, however, inconclusive.

Table 191. EMISSIONS FROM COMPRESSOR INTERNAL COMBUSTION ENGINES IN LOS ANGELES COUNTY REFINERIES (Kanter et al., 1958)

Number of compressor engines	130
Fuel gas burned, mcfd	10,500
Exhaust gas, scfm	165,000
Contaminants in exhaust gases, ppm	
Hydrocarbons	1,240
Oxides of nitrogen, as NO_2	315

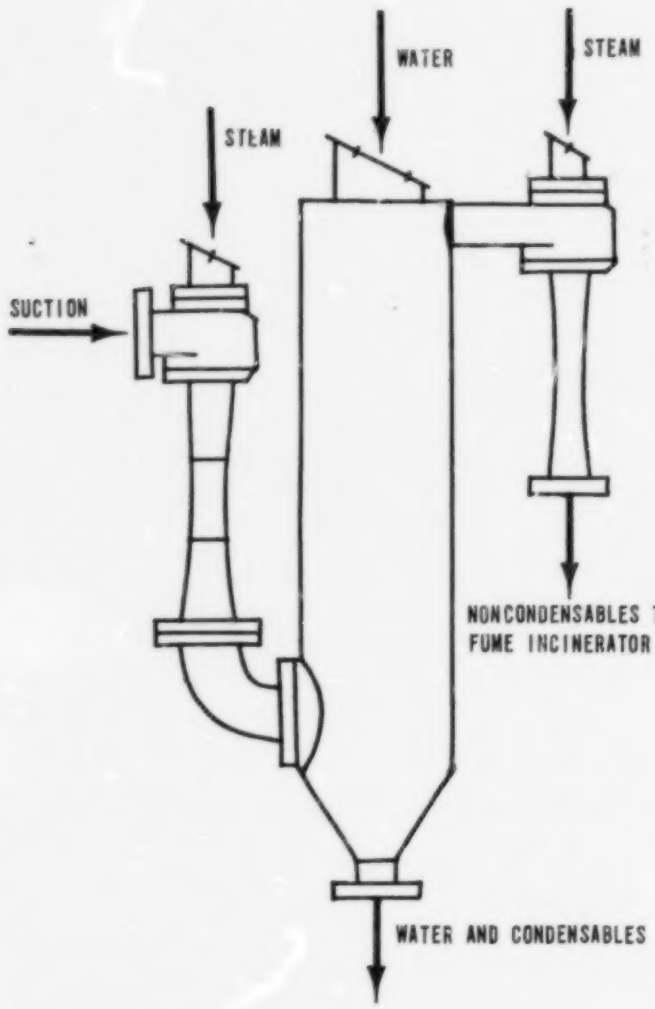


Figure 507. Schematic drawing of a two-stage, steam-actuated vacuum jet.

CHAPTER 11

CHEMICAL PROCESSING EQUIPMENT

RESIN KETTLES

HARRY E. CHATFIELD, Air Pollution Engineer

VARNISH COOKERS

HARRY E. CHATFIELD, Air Pollution Engineer

SULFURIC ACID MANUFACTURING

ROBERT J. MAC KNIGHT
Principal Air Pollution Engineer

STANLEY T. CUFFE, Air Pollution Engineer*

PHOSPHORIC ACID MANUFACTURING

EMMET F. SPENCER, JR.
Intermediate Air Pollution Engineer†

RAY M. INGELS, Air Pollution Engineer‡

PAINT-BAKING OVENS

JULIEN A. VERSSEN, Air Pollution Engineer

SOAPS AND SYNTHETIC DETERGENTS

ROBERT C. MURRAY, Senior Air Pollution Engineer

EDWIN J. VINCENT
Intermediate Air Pollution Engineer

GLASS MANUFACTURE

ARTHUR B. NETZLEY
Intermediate Air Pollution Engineer

JOHN L. MC GINNITY
Intermediate Air Pollution Engineer*

FRIT SMELTERS

JOHN L. SPINKS, Air Pollution Engineer

FOOD-PROCESSING EQUIPMENT

W. L. POLGLASE, Air Pollution Engineer

H. F. DEY, Air Pollution Engineer

ROBERT T. WALSH, Senior Air Pollution Engineer

FISH CANNERIES AND FISH REDUCTION PLANTS

ROBERT T. WALSH, Senior Air Pollution Engineer§

KARL D. LUEDTKE
Intermediate Air Pollution Engineer

LEWIS K. SMITH, Air Pollution Engineer

REDUCTION OF INEDIBLE ANIMAL MATTER

ROBERT T. WALSH, Senior Air Pollution Engineer

PAUL G. TALENS, Air Pollution Engineer

ELECTROPLATING

EMMET F. SPENCER, JR.
Intermediate Air Pollution Engineer

GEORGE THOMAS
Intermediate Air Pollution Engineer

INSECTICIDE MANUFACTURE

WILLIAM C. BAILOR, Air Pollution Engineer

JOSEPH D'IMPERIO, Air Pollution Engineer‖

HAZARDOUS RADIOACTIVE MATERIAL

WILLIAM C. BAILOR, Air Pollution Engineer

OIL AND SOLVENT RE-REFINING

JOSEPH D'IMPERIO, Air Pollution Engineer

CHEMICAL MILLING

GEORGE THOMAS
Intermediate Air Pollution Engineer

*Now with National Center for Air Pollution Control, Public Health Service, U. S. Department of Health, Education, and Welfare, Cincinnati, Ohio.
†Now with FMC Corporation, 633 Third Ave., New York, N. Y.
‡Now with State of California Vehicle Laboratories, 434 S. San Pedro St., Los Angeles, Calif.
§Now with New York-New Jersey Air Pollution Abatement Activity, National Center for Air Pollution Control, Public Health Service, U. S. Department of Health, Education, and Welfare, Raritan Depot, Metuchen, N. J.
‖Now deceased.

BLANK PAGE

CHAPTER 11

CHEMICAL PROCESSING EQUIPMENT

RESIN KETTLES

TYPES OF RESINS

A resin is defined by the American Society for Testing Materials (ASTM) as a solid or semi-solid, water-insoluble, organic substance, with little or no tendency to crystallize. Resins are the basic components of plastics and are important components of surface-coating formulations. For both uses, growth in recent years has been phenomenal; more than 5,000 companies in the United States now produce plastics.

There are two types of resins--natural and synthetic. The natural resins are obtained directly from sources such as fossil remains and tree sap. These include Congo, Batu, and East India resins from fossils; lac from insects; and damar and rosin from tree sap. Synthetic resins are those made by man.

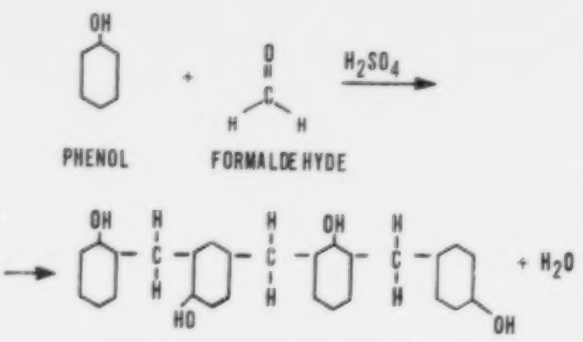
Synthetic resins can be classified by physical properties as thermoplastic or thermosetting. Thermoplastic resins undergo no permanent change upon heating. They can be softened, melted, and molded into shapes they retain upon cooling, without change in their physical properties. Thermosetting resins, on the other hand, can be softened, melted, and molded upon heating, but upon continued heating, they harden or set to a permanent, rigid state and cannot be remolded.

In this section, several synthetic resins are discussed briefly (Kirk and Othmer, 1947; Plastics Catalog Corporation, 1959; Shreve, 1956). For each, an example of ingredients is given and a typical manufacturing operation is discussed. Each basic resin type requires many modifications both in ingredients and techniques of synthesis in order to satisfy proposed uses and provide desired properties. Not all these variations, however, will be discussed since not all present individual air pollution problems.

Thermosetting resins are obtained from fusible ingredients that undergo condensation and polymerization reactions under the influence of heat, pressure, and a catalyst and form rigid shapes that resist the actions of heat and solvents. These resins, including phenolic, amino, polyester, and polyurethane resins, owe their heat-resisting qualities to cross-linked molecular structures.

Phenolic Resins

Phenolic resins can be made from almost any phenolic compound and an aldehyde. Phenol and formaldehyde are by far the most common ingredients used, but others include phenol-furfural, resorcinol-formaldehyde. and many similar combinations. Since a large proportion of phenolic-resin production goes into the manufacture of molding materials, the most desirable process for this manufacture will be described. Phenol and formaldehyde, along with an acid catalyst (usually sulfuric, hydrochloric, or phosphoric acid), are charged to a steam-jacketed or otherwise indirectly heated resin kettle that is provided with a reflux condenser and is capable of being operated under vacuum. The following formula shows the basic reaction:



PHENOL FORMALDEHYDE

TYPICAL (INTERMEDIATE) CONDENSATION PRODUCT

Heat is applied to start the reaction, and then the exothermic reaction sustains itself for a while without additional heat. Water formed during the reaction is totally refluxed to the kettle. After the reaction is complete, the upper layer of water in the kettle is removed by drawing a vacuum on the kettle. The warm, dehydrated resin is poured onto a cooling floor or into shallow trays and then ground to powder after it hardens. This powder is mixed with other ingredients to make the final plastic material. Characteristics of the molding powder, as well as the time and rate of reaction, depend upon the concentration of catalyst used, the phenol-formaldehyde ratio used, and the reaction temperature maintained.

Amino Resins

The most important amino resins are the urea-formaldehyde and melamine-formaldehyde resins. The urea-formaldehyde reaction is simple: 1 mole of urea is mixed with 2 moles of formaldehyde as 38 percent solution. The mixture is kept alkaline with ammonia pH 7.6 to 8. The reaction is carried out at 77°F for 2 days at atmospheric pressure without any reflux.

The melamine resins are made in much the same manner except that the reactants must be heated to about 176°F initially, in order to dissolve the melamine. The solution is then cooled to 77°F for 2 days to complete the reaction.

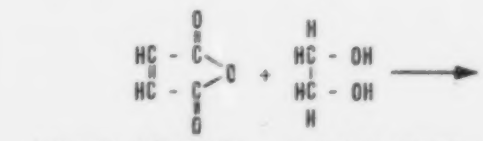
The equipment needed for the synthesis of the amino resins consists of kettles for the condensation reaction (usually nickel or nickel-clad steel), evaporators for concentrating the resin, and some type of dryer.

The amino resins are used as molding compounds, adhesives, and protective coatings, and for treating textiles and paper.

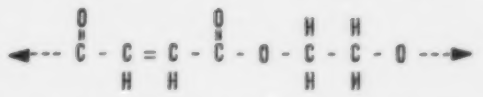
Polyester and Alkyd Resins

There is much confusion concerning the meaning of the two terms polyester and alkyd. Apparently, by chemical definition, the product obtained by the condensation reaction between a polyhydric alcohol and a polybasic acid, whether or not it is modified by other materials, is properly called a polyester. All polyesters can then be divided into three basic classes: Unsaturated polyesters, saturated polyesters, and alkyds.

1. Unsaturated polyesters are formed when either of the reactants (alcohol and acid) contains, or both contain, a double-bonded pair of carbon atoms. The materials usually used are glycols of ethylene, propylene, and butylene and unsaturated dibasic acids such as maleic anhydride and fumaric acid. A typical reaction is as follows:



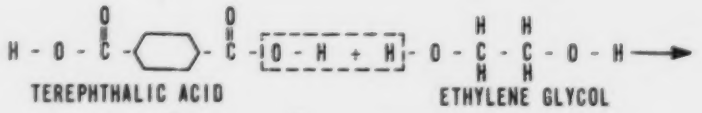
MALEIC ANHYDRIDE ETHYLENE GLYCOL



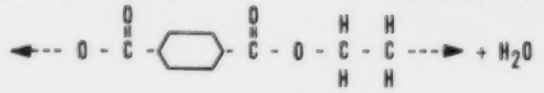
REPRESENTATIVE SEGMENT OF CHAIN-FORMED POLYESTER (REPEATING UNIT)

The resulting polyester is capable of cross-linking and is usually blended with a polymerizable material such as styrene. Under heat or a peroxide catalyst, or both, this blend copolymerizes into a thermosetting resin. It has recently found extensive use in the reinforced-plastics field where it is laminated with fibrous glass. It is also molded into many forms for a variety of uses.

2. Saturated polyesters are made from saturated acids and alcohols, as indicated by the following reaction:



TEREPHTHALIC ACID ETHYLENE GLYCOL



POLYESTER (REPEATING UNIT)

The polyesters formed are long-chain, saturated materials not capable of cross-linking. Several of these are used as plasticizers. A special type made from ethylene glycol and terephthalic acid has been made into fiber (Dacron) and film (Mylar®). Still others of this type with lower molecular weights are being used with di-isocyanates to form polyurethane resins.

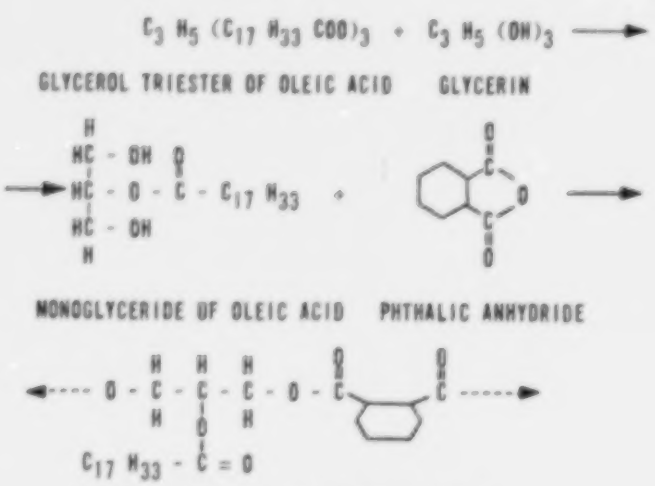
3. Alkyd resins differ from other polyesters as a result of modification by additions of fatty, monobasic acids. This is known as oil modification since the fatty acids are usually in the form of naturally occurring oils such as linseed, tung, soya, cottonseed, and, at times, fish oil. The alkyds, thinned with organic solvents, are used predominantly in the protective coating industry in varnishes, paints, and enamels.

The most widely used base ingredients are phthalic anhydride and glycerol. Smaller quantities of other acids such as maleic, fumaric, and others and alcohols such as pentaerythritol, sorbitol, mannitol, ethylene glycol, and others are used. These are reacted with the oils already mentioned to form the resin.

The oils, as they exist naturally, are predominantly in the form of triglycerides and do not react with the polybasic acid. They are changed to the reactive monoglyceride by reaction with a portion of the glycerol or other alcohol to be used. Heat and a catalyst are needed to promote this reaction,

which is known as alcoholysis. The resin is then formed by reacting this monoglyceride with the acid by agitation and sparging with inert gas until the condensation reaction product has reached the proper viscosity. The reaction takes place in an enclosed resin kettle equipped with a condenser and usually a scrubber, at temperatures slightly below 500°F. The alcoholysis can be accomplished first and then the acid and more alcohol can be added to the kettle, or all the ingredients can be added simultaneously.

An example of an alcoholysis reaction followed by reaction of the monoglyceride formed with phthalic anhydride is shown in the following:


C3 H5 (C17 H33 COO)3 + C3 H5 (OH)3
GLYCEROL TRIESTER OF OLEIC ACID
GLYCERIN
MONOGLYCERIDE OF OLEIC ACID
PHTHALIC ANHYDRIDE
REPEATING UNIT FOR OIL-MODIFIED ALKYD

Polyurethane

The manufacture of the finished polyurethane resin differs from the others described in that no heated reaction in a kettle is involved. One of the reactants, however, is a saturated polyester resin, as already mentioned, or, more recently, a polyether resin. To form a flexible foam product, the resin, typically a polyether such as polyoxypropylenetriol, is reacted with tolylene diisocyanate and water in an approximate 100: 42: 3 ratio by weight, along with small quantities of an emulsifying agent, a polymerization catalyst, and a silicone lubricant. The ingredients are metered to a mixing head that deposits the mixture onto a moving conveyor. The resin and tolylene diisocyanate (TDI) polymerize and cross-link to form the urethane resin. The TDI also reacts with the water, yielding urea and carbon dioxide. The evolved gas forms a foam-like structure. The product forms as a continuous loaf. After room temperature curing for about a day, the loaf can be cut into desired sizes and shapes, depending upon required use.

The flexible foams have found wide use in automobile and furniture upholstery and in many other specialty items.

By varying the ingredients and adding other blowing agents such as Freon 11, rigid foams with fine, close-cell structure can be formed. These can be formed in place by spraying techniques and are used extensively as insulating materials.

Thermoplastic Resins

As already stated, thermoplastic resins are capable of being reworked after they have been formed into rigid shapes. The subdivisions in this group that are discussed here are the vinyls, styrenes, and the coal tar and petroleum base resins.

Polyvinyl Resins

The polyvinyl resins are those having a vinyl ($CH=CH_2$) group. The most important of these are made from the polymerization of vinyl acetate and vinyl chloride. Other associated resins are also discussed briefly.

Vinyl acetate monomer is a clear liquid made from the reaction between acetylene and acetic acid. The monomer can be polymerized in bulk, in solution, or in beads or emulsion. In the bulk reaction, only small batches can be safely handled because of the almost explosive violence of the reaction once it has been catalyzed by a small amount of peroxide. Probably the most common method of preparation is in solution. In this process, a mixture of 60 volumes vinyl acetate and 40 volumes benzene is fed to a jacketed, stirred resin kettle equipped with a reflux condenser. A small amount of peroxide catalyst is added and the mixture is heated until gentle refluxing is obtained. After about 3 hours, approximately 70 percent is polymerized, and the run is transferred to another kettle where the solvent and unreacted monomer are removed by steam distillation. The wet polymer is then dried. Polyvinyl acetate is used extensively in water-based paints, and for adhesives, textile finishes, and production of polyvinyl butyral.

Vinyl chloride monomer under normal conditions is a gas that boils at -14°C. It is usually stored and reacted as a liquid under pressure. It is made by the catalytic combination of acetylene and hydrogen chloride gas or by the chlorination of ethylene followed by the catalytic removal of hydrogen chloride. It is polymerized in a jacketed, stirred autoclave. Since the reaction is highly exothermic and can result in local overheating and poor quality, it is usually carried out as a water emulsion to facilitate more precise control. To ensure

quality and a properly controlled reaction, several additives are used. These include an emulsifying agent such as soap, a protective colloid such as glue, a pH control such as acetic acid or other moderately weak acid (2.5 is common), oxidation and reduction agents such as ammonium persulfate and sodium bisulfite, respectively, to control the oxidation-reduction atmosphere, a catalyst or initiator like benzoyl peroxide, and a chain length-controlling agent such as carbon tetrachloride. The reaction is carried out in a completely enclosed vessel with the pressure controlled to maintain the unreacted vinyl chloride in the liquid state. As the reaction progresses, a suspension of latex or polymer is formed. This raw latex is removed from the kettle, and the unreacted monomer is removed by evaporation and recovered by compression and condensation.

A modification of the emulsion reaction is known as suspension polymerization. In this process, droplets of monomer are kept dispersed by rapid agitation in a water solution of sodium sulfate or in a colloidal suspension such as gelatin in water. During the reaction, the droplets of monomer are converted to beads of polymer that are easily recovered and cleaned. This process is more troublesome and exacting than the emulsion reaction but eliminates the contaminating effects of the emulsifying agent and other additives.

Other vinyl-type resins are polyvinylidene chloride (Saran®), polytetrafluoroethylene (fluoroethene), polyvinyl alcohol, polyvinyl butyral, and others. The first two of these are made by controlled polymerization of the monomers in a manner similar to that previously described for polyvinyl chloride. Polyvinyl alcohol has no existing monomer and is prepared from polyvinyl acetate by hydrolysis. Polyvinyl alcohol is unique among resins in that it is completely soluble in both hot and cold water. Polyvinyl butyral is made by the condensation reaction of butyraldehyde and polyvinyl alcohol. All have specific properties that make them superior for certain applications.

Polystyrene

Polystyrene, discovered in 1831, is one of the oldest resins known. Because of its transparent, glasslike properties, its practical application was recognized even then. Two major obstacles prevented its commercial development--preparation of styrene monomer itself, and some means of preventing premature polymerization. These obstacles were not overcome until nearly 100 years later.

Styrene is a colorless liquid that boils at 145°C. It is prepared commercially from ethylbenzene, which, in turn, is made by reaction of benzene with ethylene in presence of a Fridel-Crafts catalyst such as aluminum chloride. During storage or shipment the styrene must contain a polymerization inhibitor such as hydroquinone and must be kept under a protective atmosphere of nitrogen or natural gas.

Styrene can be polymerized in bulk, emulsion, or suspension by using techniques similar to those previously described. The reaction is exothermic and has a runaway tendency unless the temperature is carefully controlled. Oxygen must be excluded from the reaction since it causes a yellowing of the product and affects the rate of polymerization.

Polystyrene is used in tremendous quantities for many purposes. Because of its ease of handling, dimensional stability, and unlimited color possibilities, it is used widely for toys, novelties, toilet articles, houseware parts, radio and television parts, wall tile, and other products. Disadvantages include limited heat resistance, brittleness, and vulnerability to attack by organic solvents such as kerosine and carbon tetrachloride.

Petroleum and Coal Tar Resins

Petroleum and coal tar resins are the least expensive of the synthetic resins. They are made from the polymerization of unsaturated hydrocarbons found in crude distillate from coal tar in coke ovens or from cracking of petroleum. The exact chemical nature of these hydrocarbons has not been determined, but the unsaturates of coal tar origin are known to be primarily cyclic while petroleum derivatives are both straight- and close-chain types.

Most typical of the coal tar resins are those called Coumarone-Indene resin because these two compounds constitute a large portion of the distillate used for the reaction. The polymerization is initiated by a catalyst (usually sulfuric acid). After the reaction has proceeded as far as is desired, the unreacted monomer is removed by distillation. By controlling time, temperature, and proportions, many modifications of color and physical characteristics can be produced. The petroleum base distillate is polymerized in the same manner, yielding resins of slightly lower specific gravity than that of the coal tar resins. These resins are used in coating adhesives, in oleoresinous varnishes, and in floor coverings (the so-called asphalt tile).

Resin-Manufacturing Equipment

Most resins are polymerized or otherwise reacted in a stainless steel, jacketed, indirectly heated vessel, which is completely enclosed, equipped

with a stirring mechanism, and generally contains an integral reflux condenser (Figure 508). Since most of the reactions previously described are exothermic, cooling coils are usually required. Some resins, such as the phenolics, require that the kettle be under vacuum during part of the cycle. This can be supplied either by a vacuum pump or by a steam or water jet ejector. Moreover, for some reactions, that of polyvinyl chloride for example, the vessel must be capable of being operated under pressure. This is necessary to keep the normally gaseous monomer in a liquid state. The size of resin-processing kettles varies from a few hundred to several thousand gallons' capacity.

Because of the many types of raw materials, ranging from gases to solids, storage facilities vary accordingly--ethylene, a gas, is handled as such; vinyl chloride, a gas at standard conditions, is liquefied easily under pressure. It is stored, therefore, as a liquid in a pressurized vessel. Most of the other liquid monomers do not present any particular storage problems. Some, such as styrene, must be stored under an inert atmosphere to prevent premature polymerization. Some of the more volatile materials are stored in cooled tanks to prevent excessive vapor loss. Some of the materials have strong odors, and care must be taken to prevent emission of odors to the atmosphere. Solids, such as phthalic anhydride, are usually packaged and stored in bags or fiber drums.

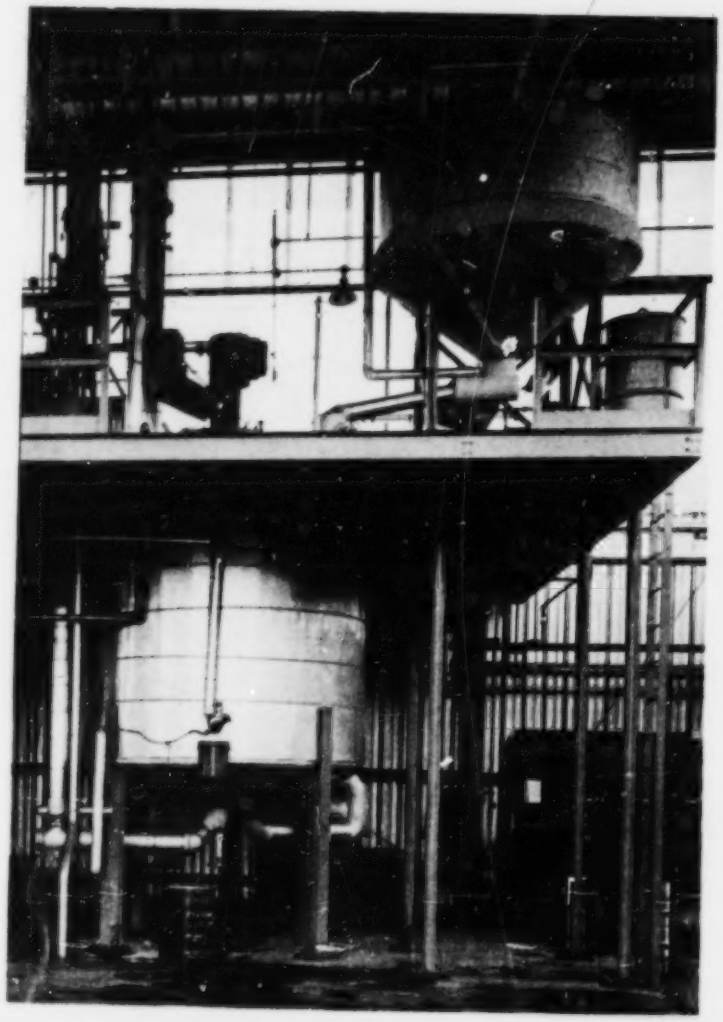


Figure 508. Typical resin-manufacturing unit showing process kettle and liquid feed tanks (Silmar Chemical Company, Hawthorne, Calif.).

Treatment of the resin after polymerization varies with the proposed use. Resins for moldings are dried and crushed or ground into molding powder. Resins, such as the alkyd resins, to be used for protective coatings are normally transferred to an agitated thinning tank, as shown in Figure 509, where they are thinned with some type of solvent and then stored in large steel tanks equipped with water-cooled condensers to prevent loss of solvent to the atmosphere (Figure 510). Still other resins are stored in latex form as they come from the kettle.

THE AIR POLLUTION PROBLEM

The major sources of possible air contamination in resin manufacturing are the emissions of raw materials or monomer to the atmosphere, emissions of solvent or other volatile liquids during the reaction, emissions of sublimed solids such as phthalic anhydride in alkyd production, emissions of solvents during thinning of some resins, and emissions of solvents during storage and handling of thinned resins. Table 192 lists the most probable types and sources of air contaminants from various resin-manufacturing operations.

In the formulation of polyurethane foam, a slight excess of tolylene diisocyanate is usually added. Some of this is vaporized and emitted along with carbon dioxide during the reaction. The TDI fumes are extremely irritating to the eyes and respiratory system and are a source of local air pollution. Since the vapor pressure of TDI is small, the fumes are minute in quantity and, if exhausted from the immediate work area and discharged to the outside atmosphere, are soon diluted to a nondetectible concentration. No specific controls have been needed to prevent emission of TDI fumes to the atmosphere.

The finished solid resin represents a very small problem--chiefly some dust from crushing and grinding operations for molding powders. Generally the material is pneumatically conveyed from the grinder or pulverizer through a cyclone separator to a storage hopper. The fines escaping the cyclone outlet are collected by a baghouse-type dust collector. The collector should be designed for a filter velocity of about 4 fpm or less.

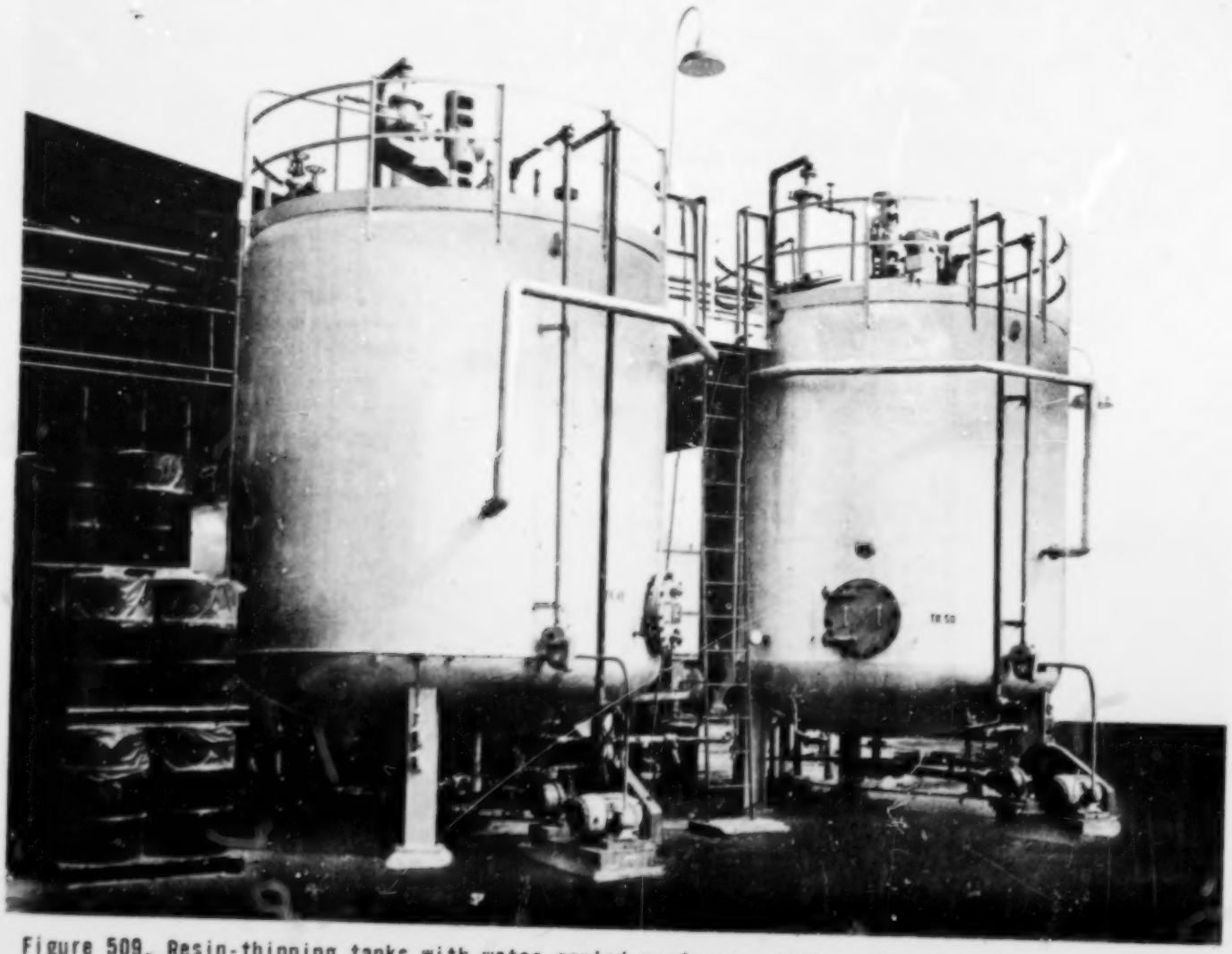


Figure 509. Resin-thinning tanks with water-cooled condensers (Allied Chemical Corp., Plastics Div., Lynnwood, Calif.).

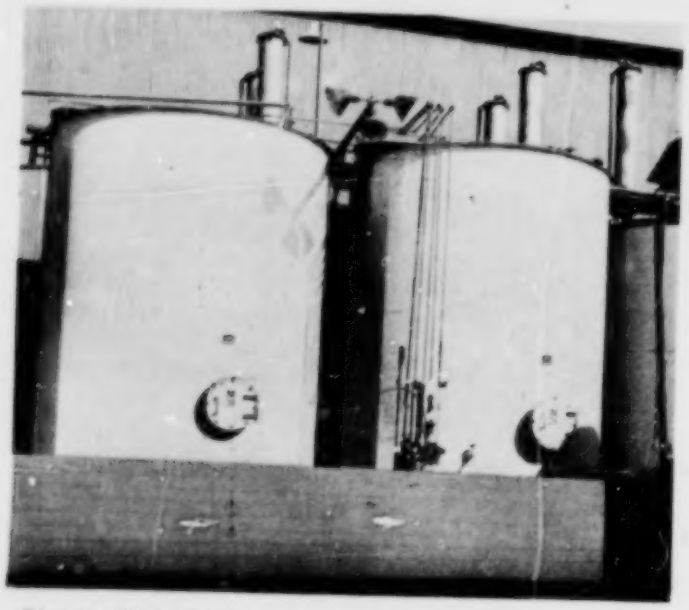


Figure 510. Resin storage tanks with condensers (Allied Chemical Corp., Plastics Division, Lynnwood, Calif.).

Most of the contaminants are readily condensable. In addition to these, however, small quantities of noncondensable, odorous gases similar to those from varnish cooking may be emitted. These are more prevalent in the manufacture of oil-modified alkyds where a drying oil such as tung, linseed, or soya is reacted with glycerin and phthalic anhydride. When a drying oil is heated, acrolein and other odorous materials are emitted at temperatures exceeding about 350°F (see further discussion under Varnish Cookers). The intensity of these emissions is directly proportional to maximum reaction temperatures. Thus, the intensity of noncondensable gases from resin formulation should be considerably less than that of gases from varnish cooking since the reaction temperature is approximately 100°F lower.

AIR POLLUTION CONTROL EQUIPMENT

Control of monomer and volatile solvent emissions during storage before the reaction and of

Table 192. PRINCIPAL AIR CONTAMINANTS AND SOURCES OF EMISSION FROM RESIN-MANUFACTURING OPERATIONS

Resin	Air contaminant	Possible sources of emission
Phenolic	Aldehyde odor	Storage, leaks, condenser outlet, vacuum pump discharge
Amino	Aldehyde odor	Storage, leaks
Polyester and alkyds	Oil-cooking odors Phthalic anhydride fumes Solvent	Uncontrolled resin kettle discharge Kettle or condenser discharge
Polyvinyl acetate	Vinyl acetate odor Solvent	Storage, condenser outlet during reaction, condenser outlet during steam distillation to recover solvent and unreacted monomer
Polyvinyl chloride	Vinyl chloride odor	Leaks in pressurized system
Polystyrene	Styrene odor	Leaks in storage and reaction equipment
Petroleum and coal tar resins	Monomer odors	Leaks in storage and reaction equipment
Polyurethane resins	Tolylene diisocyanate	Emission from finished foam resulting from excess TDI in formulation

solvent emissions during thinning and storage after the polymerization of the resin is relatively simple. It involves care in maintaining gastight containers for gases or liquefied gases stored under pressure, and condensers or cooling coils on other vessels handling liquids that might vaporize. Since most resins are thinned at elevated temperatures near the boiling point of the thinner, resin-thinning tanks, especially, require adequate condensers. Aside from the necessity for control of air pollution, these steps are needed to prevent the loss of valuable products.

Heated tanks used for storage of liquid phthalic and maleic anhydrides should be equipped with condensation devices to prevent losses of sublimed material. An excellent device is a water-jacketed, vertical condenser with provisions for admitting steam to the jacket and provisions for a pressure relief valve at the condenser outlet set at perhaps 4 ounces' pressure. During storage the tank is kept under a slight pressure of about 2 ounces, an inert gas making the tank completely closed. During filling, the displaced gas, with any sublimed phthalic anhydride, is forced through the cooled condenser where the phthalic is deposited on the condenser walls. After filling is completed, the condensed phthalic is remelted by passing steam through the condenser jacket.

Addition of solids such as phthalic anhydride to other ingredients that are above the sublimation temperature of the phthalic anhydride causes temporary emissions that violate most air pollution standards regarding opacity of smoke or fumes. These emissions subside somewhat as soon as the solid is completely dissolved but remain in evidence at a reduced opacity until the reaction has been completed. The emissions can be controlled fairly easily with simple scrubbing devices. Various types of scrubbers can be used. A common system that has been proved effective consists of a settling chamber, commonly called a resin slop tank, followed by an exhaust stack equipped with water sprays. The spray system should provide for at least 2 gallons per 1,000 scf at a velocity of 5 fps. The settling chamber can consist of an enclosed vessel partially filled with water capable of being circulated with gas connections from the reaction vessel and to the exhaust stack. Some solids and water of reaction are collected in the settling tank, the remainder being knocked down by the water sprays in the stack. Another example is shown in Figure 511. Here the vapors from a polyester resin process kettle are first passed through a spray chamber-type precleaner followed by a venturi scrubber. This system effectively reduces visible emissions. Scrubber water may be recirculated or used on a once-through basis, depending primarily upon the available waste-water disposal system. The scrubber water can be odorous and should be discharged to a sanitary sewer.

Many resin polymerization reactions, for example, polyvinyl acetate by the solution method, require

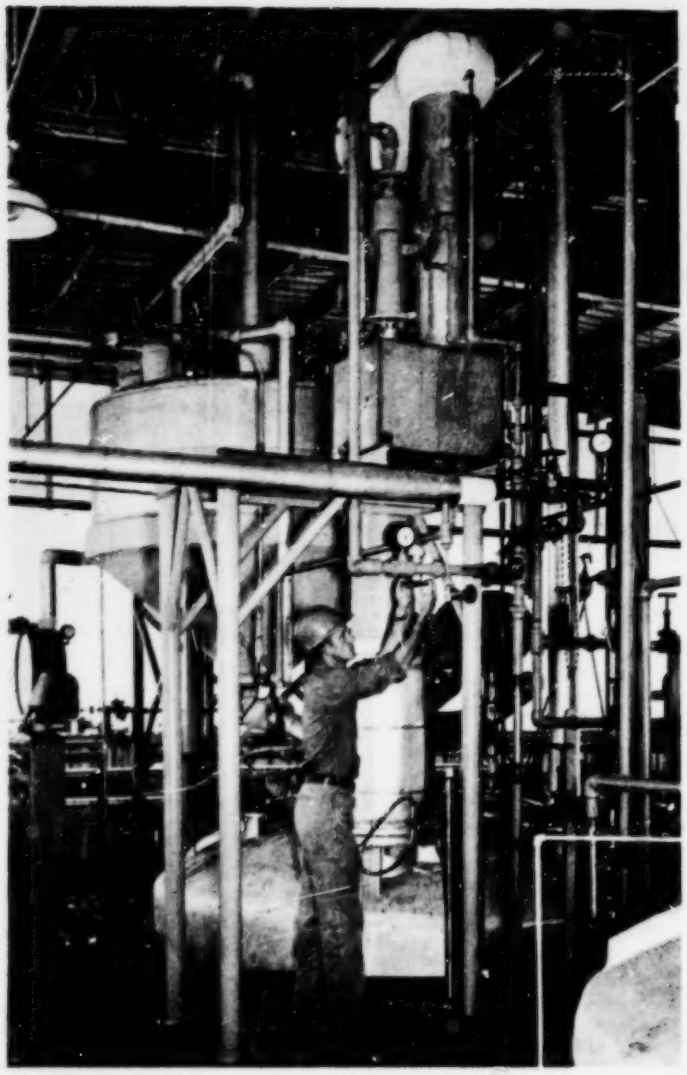


Figure 511. Venturi scrubber venting resin-manufacturing equipment (Silmar Chemical Corporation, Hawthorne, Calif.).

refluxing of ingredients during the reaction. Thus, all reactors for this or other reactions involving the vaporization of portions of the reactor contents must be equipped with suitable reflux- or horizontal-type condensers or a combination of both. The only problems involved here are proper sizing of the condensers and maintaining the cooling medium at the temperature necessary to effect complete condensation.

When noncondensable, odor-bearing gases are emitted during the reaction, especially with alkyd resin production as already mentioned, and these gases are in sufficient concentration to create a public nuisance, more extensive air pollution control equipment is necessary. These are discussed thoroughly under other sections concerning odors (Varnish Cookers and Reduction of Inedible Animal Matter) and include equipment for absorption and chemical oxidation, adsorption, and combustion, both catalytic and direct-flame type.

VARNISH COOKERS

INTRODUCTION

Varnish as a finished product is defined as a transparent, homogeneous, heat-processed blend of drying oil, resin, drier, and solvent. When the varnish is applied as a thin film, the solvent evaporates, and the remaining materials oxidize and polymerize to form a hard, solid, continuous, transparent coating (Kirk and Othmer, 1947). In the protective coating industry, the term varnish is also used to describe a base or vehicle for pigmented coatings. In this form, the drier and most of the solvent are usually omitted until the final formulation of the pigmented coating.

The uses of varnish are many and varied. It is commonly used where a transparent coating is desired for visible surfaces such as furniture and floor coatings and overprint for paper labels. In other applications, the surface is not visible, but varnish is more economical and gives better protection than pigmented coatings do. These include metal-container coatings, insulating varnishes, and bottle cap liners.

Historically, varnish meant one type of product, the oleoresinous varnish (oil plus resin). This product, by definition, was also required to dry to a transparent film. Recently, many other products have been developed that are called varnishes but do not meet the requirements of this definition. Some of the most important ones are now listed.

1. Spirit varnish is a solution of a resin with little or no oil in a volatile solvent. It normally dries to a hard, brittle finish. The most common varnish of this type is shellac, which is a solution of the natural lac resin in denatured alcohol.

2. Alkyd resin varnish is a solution of alkyd resin in a volatile solvent with added drier. It is similar to conventional varnish in that an oil-modified alkyd resin is used. There is a marked difference between alkyd resin varnish and oleoresinous varnish in their raw materials and in their manufacturing processes. The alkyd varnishes, however, have properties similar to those of oleoresinous varnishes and are used primarily for the same purposes.

3. Asphalt varnish is a solution of asphalt in volatile solvent. It is formed at high temperatures of 300° to 500°F and is used as black enamel where low cost and excellent chemical resistance are desired.

4. Lithograph varnish is manufactured from linseed oil, which is oxidized and polymerized to higher viscosity and then blended with drier and resin. It is used as a vehicle for pigmented lithographing printing ink.

Raw Materials for Varnish Making

Oleoresinous varnishes, in their final form ready for application as surface coatings, are composed of four groups of materials: Resins, oils, solvents, and driers.

The varnish-making resins are hard, brittle, noncrystalline solids that usually melt and dissolve in organic solvent. Their functions in the formulation are to contribute to the drying speed, hardness, toughness, and gloss. The resins most commonly used are the natural resins, such as Rosin, Congo, Batu, East India, Dammar, and Lac; the semisynthetic or modified natural resins, which include the metallic resins and ester gum; and the synthetic resins such as phenolics, modified phenolic, maleic, terpene, and the coal tar and petroleum-based resins.

The drying oils are liquid substances that oxidize and polymerize in the atmosphere to form hard, dry, resinous solids. They help give the final varnish product its flexibility, adhesion, and durability. The most extensively used are the naturally occurring fatty oils such as linseed, tung or China wood, safflower, soybean, and cottonseed. Also used in fair quantities are fish oil and tall oil, which is a blend of oil and resin acid recovered from the black liquor in the manufacture of pulp by the sulfate process.

Solvents are used in varnish formulation to reduce the viscosity of the material so that it can be applied as a thin film. The solvent evaporates upon application and is not a permanent part of the finish. Solvents vary widely both in drying time and in ability to dissolve various resins. In general, aliphatic hydrocarbons such as kerosine and mineral spirits are classed as low-power solvents while the aromatics such as toluene and xylene are high-power solvents. The types and quantities of solvent to be used for a specific formulation can be determined only after consideration of the type of resin used, the percent solids and viscosity of the finished product, and the characteristics required.

Driers are added to catalyze the oxidation and promote polymerization of the film after application. They may be added to the other ingredients during cooking or, more commonly, to the finished product. The driers used are soaps of heavy metals such as lead, cobalt, or manganese. In order of importance are naphthenates, tallates, octoates, linoleates, and resinates of these heavy metals.

Manufacturing Processes Involving Heat

In the manufacture of varnish products, the application of heat to a single ingredient or to a mixture of ingredients is the most important single operation. Heating performs many functions, depending upon the raw materials used and the point in the formulation cycle. Several of the most important of these functions follow:

1. Polymerization. Probably the most important purpose in heating the ingredients in a varnish is to polymerize the oil. The presence of the resins has essentially no effect except to slow the polymerization reaction. For a fast-polymerizing oil such as China wood, the resin may be added early in order to make the reaction more controllable. When a slower oil such as linseed is used the resin may be added after the polymerization (or bodying, as it is called) has nearly progressed to the desired viscosity point. This method is preferable for slow oils since prolonged contact of oil and resins in bodying tends to result in a darker product.

2. Depolymerization. Some natural resins are so high in molecular weight that they are insoluble in drying oil. By heating these resins to a relatively high temperature, 600° to 650°F, the resin structure breaks down with a resultant loss of 10 to 30 percent of the original resin. The remaining resin is then readily soluble in the drying oils and can be processed to a finished varnish product. This heating procedure is commonly known as gum running.

3. Melting and accelerated solution. The temperatures used in varnish cooking are high enough to make the viscous and solid ingredients fluid and easily blendable. Moreover, the solvent is easier to incorporate into the cooked products at an elevated temperature.

4. Esterfication. In varnish making, rosin or tall oil is treated with a polyhydric alcohol to form an ester. Glycerol and pentaerythritol are typical alcohols used. Reaction temperatures during this operation are 450° to 525°F.

5. Gas checking or isomerization. Some of the more active oils, such as China wood oil, dry to partially crystalline films. This fault is eliminated by heating the oil to 450° to 580°F. Apparently, this heating changes the location of the double bond in the molecule to a less reactive position, which thereby eliminates extreme reactivity during oxidation but does not drastically affect the polymerization rate.

6. Distillation and evaporation. Distillation and evaporation are used to remove from formulation some of the undesirable constituents such as volatile constituents of resins that have been subjected to gum running, excess glycerol, and water. These materials may be condensed and recovered or removed with the remainder of the varnish fumes.

Major Types of Manufacturing Equipment

Varnish cooking is accomplished in two types of vessels--the old open kettle and the newer, totally enclosed, stationary kettle.

The portable open kettle is cylindrical, has a flat bottom, rests upon a three- or four-wheel truck, and is heated over an open flame. This type kettle usually varies in capacity from 150 to 370 gallons and is made of steel, copper, monel, aluminum, or stainless steel. Under normal operating conditions, the kettle is charged in the loading room, moved to the fire pit, heated, then transferred to another location for cooling, and finally to still another location for addition of thinner and drier. In some operations involving open-kettle cooking, a portable electric mixer is used or, even more crudely, the mixing is done manually. Figure 512 shows a kettle of this type.

The more modern equipment consists of a totally enclosed, autoclave-type kettle set over or within a totally enclosed source of heat. The kettle is usually in the shape of a cylinder with dome-shaped top and bottom, is normally constructed of stainless steel, and has completely automatic controls. Heat is supplied by natural gas, oil, electric coils, circulating Dowtherm, or hot oil. Liquid raw materials are pumped directly and solids are added through a manhole at the top, which can be sealed. During the operation, the unit is completely enclosed and usually supplied with an inert atmosphere such as nitrogen or carbon dioxide. The kettle is also usually equipped with cooling coils to cool the end prod-

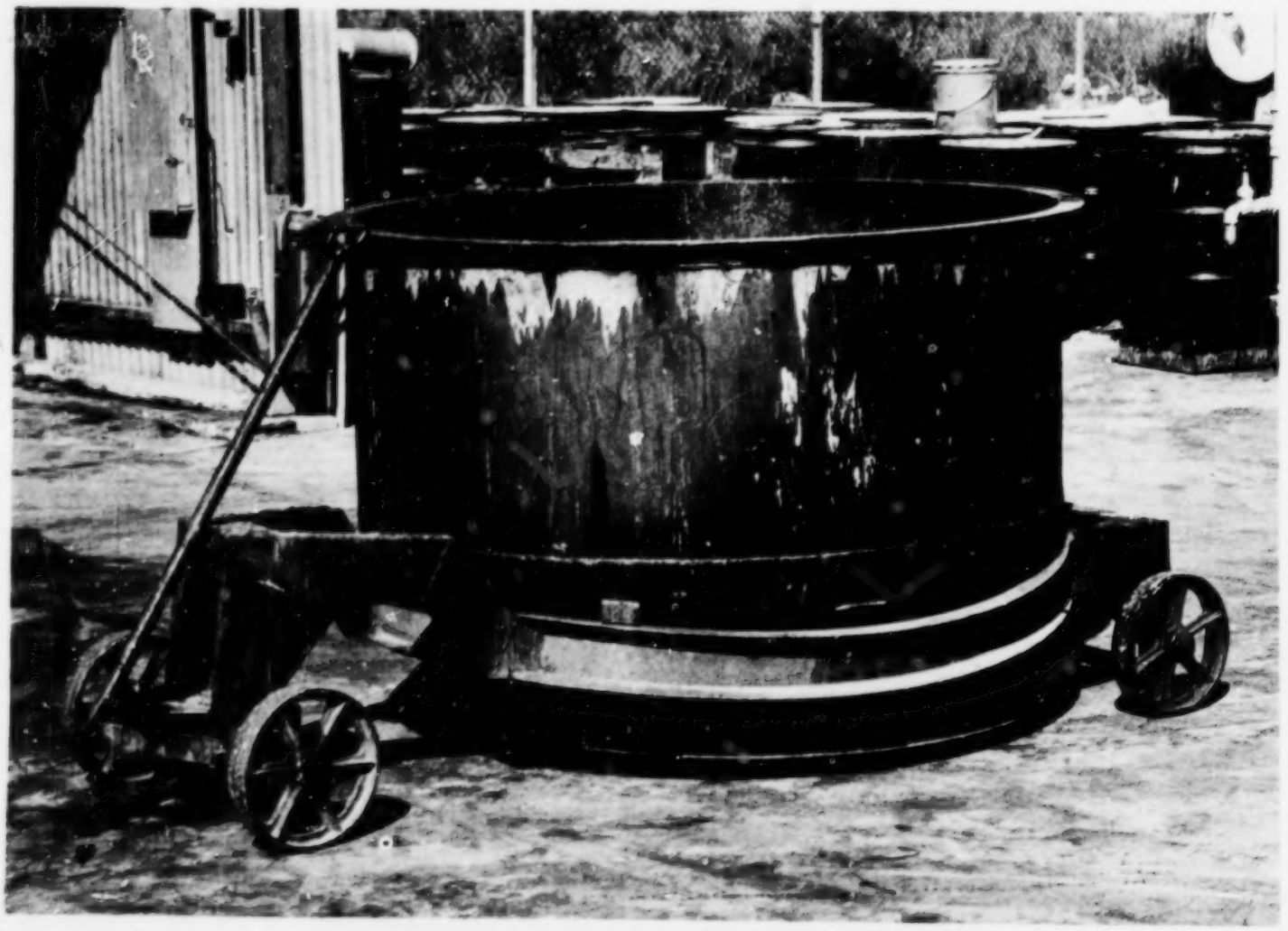


Figure 512. Uncontrolled open kettle for varnish cooking.

uct quickly or prevent the exothermic polymerization reaction from ruining a batch. Finished material is pumped to other tanks equipped with agitators and integral condensers for thinning.

Variations in Varnish Formulation

There appear to be as many different varnish formulations as there are enterprises making varnish. Minor deviations in formulation exist among varnishes to be used for the same purpose, in addition to the major deviations in formulation that exist among varnishes according to their ultimate uses.

A time-honored varnish formula is described as follows (Von Fisher, 1948): 40 gallons of China wood oil are heated rapidly to about 575°F to gasproof the oil and body it slightly. One-hundred pounds of ester gum are then added, which cools the oil and slows and controls its tendency to gel rapidly. The varnish base is then cooled to about 400°F, at which temperature mineral spirits can be added to bring the finished varnish to a viscosity of about 1 to 2 poises and a nonvolatile content of 50 to 60 percent. To this finished varnish, some antiskinning agents and driers, usually lead and cobalt, are added.

Various modifications of this basic recipe have been used since the advent of synthetic resins. Replacement of the ester gum with a pure phenol-formaldehyde resin adds substantially to the durability of the finished varnish. Other modifications include replacement of the glycerin ester of rosin with pentaerythritol, which not only aids drying but also improves the durability of the varnish; and addition of maleic anhydride and fumaric acid, which improve durability even more. A typical varnish formulation, described as a general-purpose utility varnish, is shown in Table 193.

Table 193. TYPICAL MODERN VARNISH FORMULATION

Constituent	Quantity, lb
Tall oil	1,000
Dehydrated castor oil	405
Pentaerythritol	136
Maleic anhydride	40
Mineral spirits	1,530
Lead naphthenate	30
Cobalt naphthenate	10
Manganese naphthenate	5
Total	3,156

THE AIR POLLUTION PROBLEM

Varnishes are cooked and oils bodied at temperatures of from 200° to 600°F. At about 350°F the products begin to decompose, resulting in the emission of decomposition products from the cooking vessel. As long as the cooking is continued above this temperature, the emissions continue, the maximum rate occurring shortly after the maximum temperature has been reached. These cooks average 8 to 12 hours. The quantity, composition, and rate of emissions depend upon the ingredients in the cook, the maximum temperature, method of introducing additives, degree of stirring, cooking time, and extent of air or inert gas blowing (Stenburg, 1958). Total emissions for oleoresinous varnishes average from 3 to 6 percent, and those from oil cooking and blowing, 1 to 3 percent.

Cooker emissions vary in composition, depending upon the ingredients in the cook. Mattiello (1943) states that compounds emitted from cooking of oleoresinous varnish include water vapor, fatty acids, glycerine, acrolein, phenols, aldehydes, ketones, terpene oils, terpenes, and carbon dioxide. Bodying oils emit these same compounds less the phenols, terpene oils, and terpenes. Gum running yields water vapor, fatty acids, terpenes, terpene oils, and tar. Besides the air contaminants listed by Mattiello, some highly offensive sulfur compounds such as hydrogen sulfide, allyl sulfide, butyl mercaptan, and thiophene are formed when tall oil is esterfied with glycerine and pentaerythritol, and these compounds are emitted as a result of small amounts of sulfur in the tall oil. Attempts to alleviate this problem involve further refining tall oil to remove as much sulfur as possible. At times, rapid cooling of the cook is necessary because of lack of temperature control or to the nature of the particular product. This rapid cooling is sometimes done by injecting water directly into the mixture. In this case, unless extreme care is taken, the rapid emission of water vapor can entrain sizable amounts of liquid droplets.

Of all these compounds emitted, acrolein is the one most generally associated with oil cooking because of its pungent, disagreeable odor and irritating characteristics. Some of the more odorous compounds have very low odor thresholds; acrolein, for example, has a threshold at 1.8 ppm and some of the sulfur compounds have a threshold at about 0.001 ppm.

Although they are not from the varnish cook, emissions of thinning solvent are important air contaminants to be considered from varnish manufacturing. In most of the newer installations, the cooked varnish is pumped to a thinning tank that is equipped with integral conden-

sers. In this equipment the emissions of solvent are kept to a minimum. In the older open-kettle operations, however, the thinning operation is carried out near the boiling point of the solvent, and emissions of vapor can be considerable. In this case, the thinning tank can be hooded and the vapors ducted to the same exhaust system that removes the fumes from the cooking kettles. In the design of air pollution control equipment for these operations, the emissions of solvent as well as the emissions from the cooker should be considered. From the viewpoint of amount of air pollution, the emissions of solvent are more important. Emissions from the cooker constitute essentially a local nuisance problem because of odors while the emissions of solvent contribute to the overall hydrocarbon concentration in the atmosphere. In general, the emissions of solvent in varnish-cooking operations amount to 1 to 2 percent by weight of the solvent used.

In addition to the emissions of vapor and fume, the addition of solid material to a varnish cook may cause short bursts of dust emissions. For example, when phthalic anhydride is added to a cook that is above the compound's sublimation temperature, considerable dust is created.

HOODING AND VENTILATION REQUIREMENTS

For the control methods to succeed, the fumes must be captured and conveyed to the control device. The exhaust system should be designed to remove the fumes from the kettles under all operating conditions without hindering kettle operation. For open kettles, the hood should fit closely enough to prevent excess entraining air. Bidlack and Fasig (1951) state that a 1,000-gallon closed kettle should be provided with an exhaust capacity of 300 to 400 cfm, and a standard open kettle, with 800 to 1,000 cfm. Air volumes for open kettles have been shown to be reduced to approximately 200 cfm if the hooding is properly designed. Figure 513 shows retractable hoods in place over open, portable kettles. These hoods have openings for addition of material and for thermometers and agitators. The large opening for adding material should have a hinged cover that can be kept closed except when additions are actually being made. An indraft velocity of about 150 fpm must be maintained through the hood openings to prevent leakage of contaminants. Condensate that collects on the inner surface of the hood should be collected in an outer trough and drained to a container.

The main ductwork problems are corrosion and fouling. The corrosion can be overcome by installing stainless steel ductwork. In installations processing alkyd resins, especially where solid phthalic or maleic anhydride or pentaerythritol is added, deposition of material in the ductwork is heavy and results in plugging in a relatively short time. For these systems, rectangular ducts are preferable, with one side hinged or removable to facilitate cleaning.

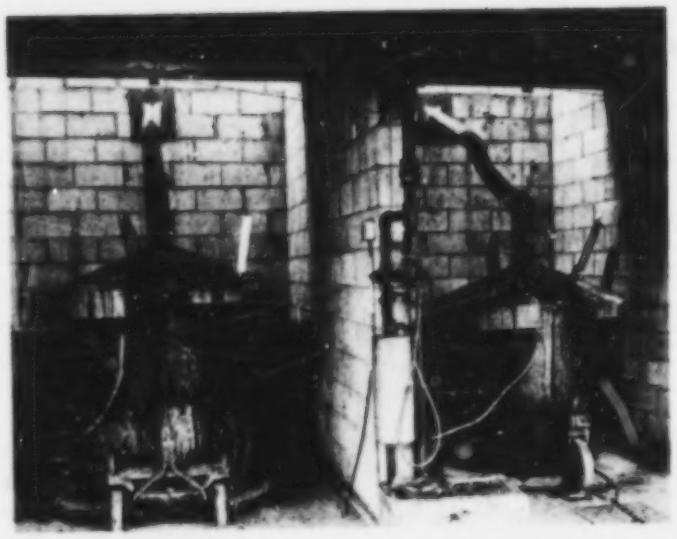


Figure 513. Open varnish-cooking kettles with exhaust hoods (Standard Brand Paints Company, Torrance, Calif.).

Conveying velocities of 1,500 to 2,000 fpm in the ductwork are usually satisfactory.

AIR POLLUTION CONTROL EQUIPMENT

All operations in which varnish is cooked or drying oils are bodied by application of heat, with or without blowing with air or inert gases, should have air pollution control devices. Of the total material charged to an uncontrolled kettle, 1 to 5 percent is discharged to the atmosphere during the cook. This material includes the odorous, irritating compounds previously mentioned. The control devices applicable to varnish cooking are the same as those used for controlling other odor sources, with some modifications to meet situations unique to this operation. In addition to odor sources, visible emissions must also be eliminated.

Scrubbers

Scrubbing and condensing equipment is not capable of controlling varnish odors adequately because most of the objectionable material is in the form of noncondensable or insoluble gas or vapor, or is particulate matter of very small size. Scrubbers are, however, valuable adjuncts when used as precleaners.

Microscopic examination of particles deposited on glass slides held in the path of emissions

from a varnish-cooking operation showed a particle size range from 2 to 20 microns' diameter. The most frequent sizes were 8 to 10 microns. Scrubbers have little effect on most of these small particles. Scrubbers do, however, control emissions of sublimed solids such as phthalic anhydride. This material solidifies into relatively large flakes that are fairly easy to control.

The scrubbing equipment used upstream from the final collection device is generally a spray tower, a plate tower, a chamber or tower with a series of baffles and water curtains, an agitated tank, or a water jet scrubber. The spray tower is probably the most efficient because the high degree of atomization that can be obtained in the scrubbing liquid by the sprays allows for maximum contact between the scrubbing water and particulate matter. A major disadvantage of the spray tower, however, is the excessive maintenance required to keep the spray nozzle free from clogging and in proper operation if the scrubbing media are recirculated. From an economic point of view, the baffled water curtain scrubber is better but is less efficient. Packed towers are not usually used in varnish operations, because of the gummy condensed fumes that rapidly plug the tower. In practically all the scrubbing devices, the flow of vapor is countercurrent to that of the scrubbing liquid. Although various liquids have been used as scrubbing media, for example, acids, bases, various oils, and solvents, all are too expensive to be used in large-scale operations. Water is generally used and is usually not recirculated. Wetting agents are at times added to the water to increase its efficiency as an absorbent.

Adsorbers

Adsorbing equipment, especially activated-carbon filters, are very efficient in removing solvents and odors from gas streams. To maintain this efficiency, however, the gas stream entering the carbon filters must be almost completely free of solids and entrained oil droplets. Unfortunately, varnish cooker effluent is not free of these materials. Without some highly efficient precleaning device, an activated-carbon filter serving a varnish cooker would rapidly become clogged and inoperative. If used downstream from an efficient filter or precipitator, an activated-carbon unit could control solvents and odors effectively. The economy of this combined system is, however, questionable compared to that of combustion in terms of both the original cost and the operating cost. Activated carbon has recently received a fair amount of attention in operations involving the control of emissions of solvents. Here, the economics of the operation are greatly enhanced by the possibility of solvent recovery. Thus, a relatively high initial installation cost could be recovered in a short period. This economic lever does not exist for cooking operations, however, and as far as can be determined, little, if any, emissions from varnish cooking have been controlled by adsorption.

Afterburners

At present, combustion is the only control method that has proved effective. The other methods listed individually remove varying amounts of the contaminants from varnish cooking, but a properly designed afterburner can do the job alone. In some instances, using a scrubber as a precleaner may be desirable from an operational point of view.

Afterburners that have been used for controlling emissions from varnish cookers have been predominantly of the direct-flame type, effluent gases and flame entering tangentially, as shown in Figure 514, or the axially fired type shown

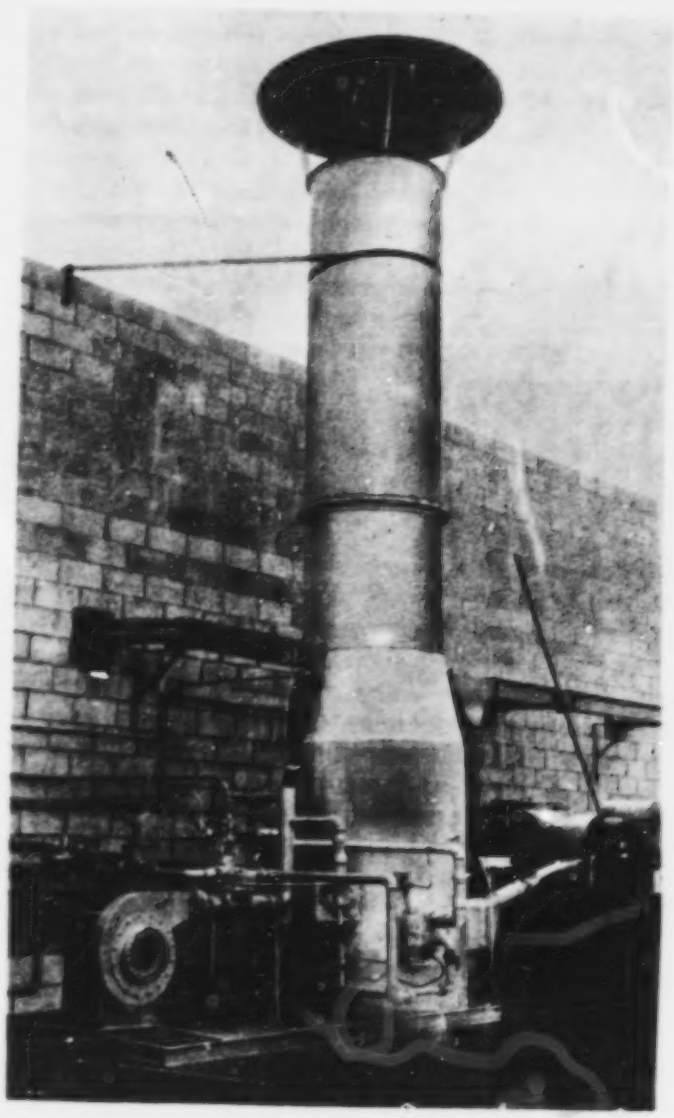


Figure 514. Tangentially fired vertical afterburner (Major Paint Co., Division of Standard Brands Paint Co., Torrance, Calif.).

in Figure 515. The burners are normally designed to be capable of reaching a temperature of 1,400°F under maximum load conditions. For most operations, however, 1,200°F completely controls all visible emissions and practically all odors. At temperatures appreciably below 1,200°F, incomplete combustion results in intermediate products of combustion, and highly odorous materials are emitted. Table 194 summarizes results of stack tests on two types of direct-flame afterburners.

The afterburner should be designed to have the maximum possible flame contact with the gases to be controlled and it should be of sufficient size to have a gas retention time of at least 0.3 second. Most authorities agree that the length-to-diameter ratio should be about 2.5 to 4:1. In order to prevent flashback and serious fire hazard, the fumes must enter the afterburner at a velocity faster than the flame propagation rate in the reverse direction. An even more positive fire control is a flame trap or barrier between the afterburner and the kettle. This could be a simple scrubber, as shown in the schematic plan of a control system in Figure 516. Mills et al. (1960) describe the optimum design features of direct-flame afterburners used specifically for varnish cookers.

Table 194. SUMMARY OF RESULTS OF STACK DISCHARGE TESTS OF TWO TYPES OF AFTERBURNERS SERVING VARNISH-COOKING KETTLES

	Unit A	Unit B
Firing method	Tangential	Axial
Air entry	Tangential	Tangential
Mixing method	Orifice	Baffle
Number of kettles exhausted during test	2	2
Material processed	Alkyd Spar varnish	Linseed oil
Exhaust system volume, scfm	950	320
Gas fuel use, cfm fuel per cfm exhaust air	0.32	0.027
Combustion chamber		
Average velocity, fps	15	12
Length-to-diameter ratio	4	2
Mixing velocity, fps	29	17.5
Average temperature, °F	1,220	1,100
Residence time, sec	0.7	0.3
Efficiency of removal, %		
Particulate matter	94	88
Organic acids	50	No data
Hydrocarbons	99+	96

Catalytic afterburners have been used to control emissions from varnish cookers in some sec-

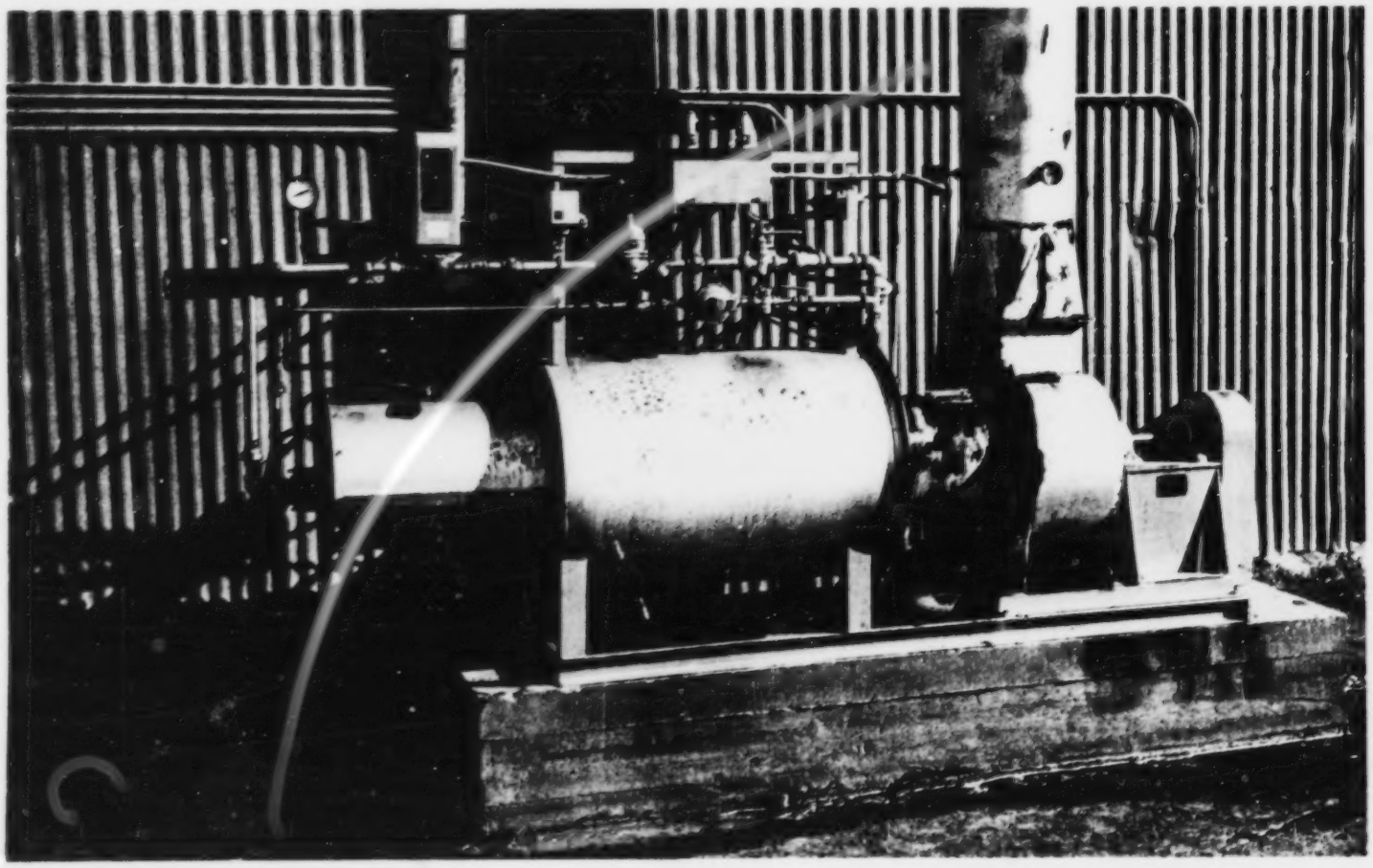


Figure 515. Axially gas-fired afterburner with induced-draft fan (McCloskey Varnish Co. of the West, Los Angeles, Calif.).

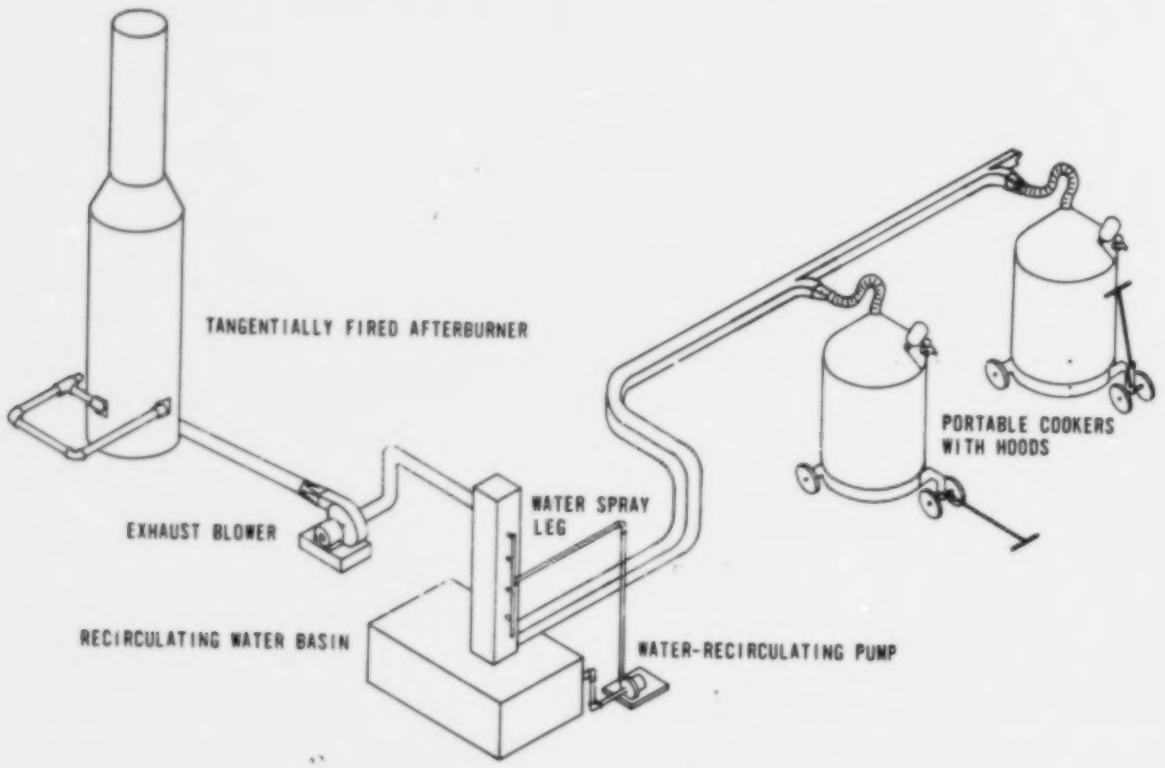


Figure 516. Schematic plan for varnish-cooking control system.

tions of the United States. Some references to these installations have indicated satisfactory performance. They have not been used in the southern California area. Catalytic units have, however, been used considerably for controlling emissions of solvent from sources such as tin plate-coating operations. Temperatures near 950°F at the catalyst outlet have been adequate to control visible emissions and some odors from these operations. The effluent from varnish cookers could probably be incinerated to about the same degree at the same temperature range as that of the solvent from metal coating. Although few analytical results have been located, Selheimer and Lance (1954) report that laboratory-scale, catalytic-combustion tests on varnish-cooking effluent was considered satisfactory at about 700°F. They report 800°F as necessary to burn phthalic anhydride fumes, and their tests indicate an inability to incinerate pentaerythritol properly. This latter result has been refuted by manufacturers of catalytic units, but no specific data have been provided.

SULFURIC ACID MANUFACTURING

Sulfuric acid is used as a basic raw material in an extremely wide range of industrial processes and manufacturing operations. Because of its widespread usage, sulfuric acid plants are scattered throughout the nation near every industrial complex.

Basically, the production of sulfuric acid involves the generation of sulfur dioxide (SO_2), its oxidation to sulfur trioxide (SO_3), and the hydration of the SO_3 to form sulfuric acid. The two main processes are the chamber process and the contact process. The chamber process uses the reduction of nitrogen dioxide to nitric oxide as the oxidizing mechanism to convert the SO_2 to SO_3. The contact process, using a catalyst to oxidize the SO_2 to SO_3, is the more modern and the more commonly encountered. For these reasons further discussion will be restricted to the contact process of sulfuric acid manufacture.

CONTACT PROCESS

A flow diagram of a "Type S" (sulfur-burning, hot-gas purification type) contact sulfuric acid plant is shown in Figure 517. Combustion air is drawn through a silencer, or a filter when the air is dust laden, by either a single-stage, centrifugal blower or a positive-pressure-type blower. Since the blower is located on the upstream side, the entire plant is under a slight pressure, varying from 1.5 to 3.0 psig. The combustion air is passed through a drying tower before it enters

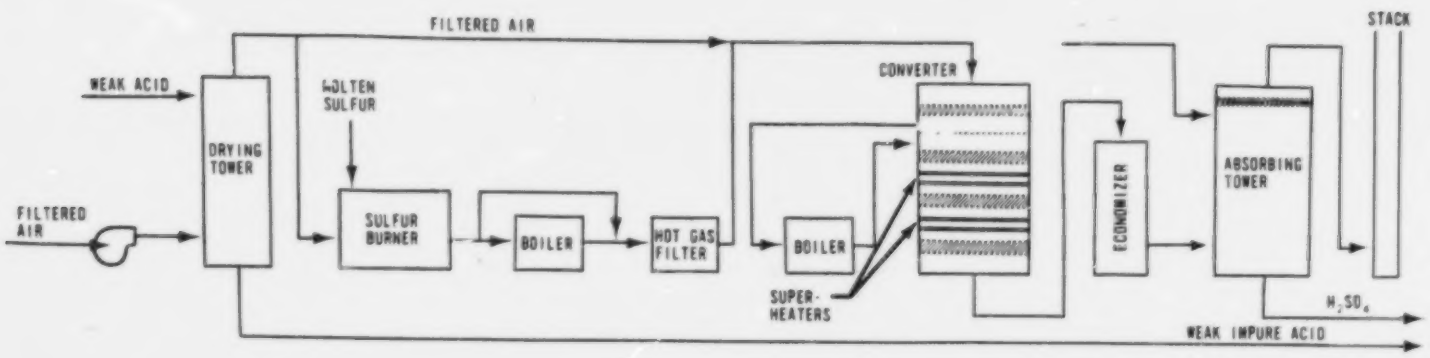


Figure 517. Flow diagram of a typical "Type S" sulfur-burning contact sulfuric acid plant.

the sulfur burner. In the drying tower, moisture is removed from the air by countercurrent scrubbing with 98 to 99 percent sulfuric acid at temperatures from 90° to 120°F. The drying tower has a topside internal-spray eliminator located just below the air outlet to minimize acid mist carryover to the sulfur burner.

Molten sulfur is pumped to the burner where it is burned with the dried combustion air to form SO_2. Normally a gas containing approximately 9 percent SO_2 is produced in a Type S plant. The combustion gases together with excess air leave the burner at about 1,600°F and are cooled to approximately 800°F in a water tube-type waste-heat boiler. The combustion gases then pass through a hot-gas filter into the first stage or "pass" of the catalytic converter at between 750° and 800°F to begin the oxidation of the SO_2 to SO_3. If the molten sulfur feed has been filtered at the start of the process, the hot-gas filter may be omitted. Because the conversion reaction is exothermic, the gas mixture from the first stage of the converter is cooled in a smaller waste-heat boiler. Gas cooling after the second and third converter stages is achieved by steam superheaters. Gas leaving the fourth stage of the converter is partially cooled to approximately 450°F in an economizer. Further cooling takes place in the gas duct before the gas enters the absorber. The extent of cooling required depends largely upon whether or not oleum is to be produced. The total equivalent conversion from SO_2 to SO_3 in the four conversion stages is about 98 percent. Table 195 shows typical temperatures and conversions at each stage of the four-stage converter. These figures vary somewhat with variations in gas composition, operating rate, and catalyst condition.

The cooled SO_3 combustion gas mixture enters the lower section of the absorbing tower, which is similar to the drying tower. The SO_3 is absorbed in a circulating stream of 99 percent sulfuric acid. The nonabsorbed tail gases pass overhead through mist removal equipment to the exit gas stack (Duecker and West, 1959).

Table 195. TEMPERATURES AND CONVERSIONS IN EACH STAGE OF A FOUR-STAGE CONVERTER FOR A "TYPE S" SULFUR-BURNING CONTACT SULFURIC ACID PLANT

Location of gas	Temperatures, °C	°F	Equivalent conversion, %
Entering 1st pass	410	770	
Leaving 1st pass	601.8	1,115	
	191.8	345	74.0
Entering 2d pass	438	820	
Leaving 2d pass	485.3	906	
	47.3	86	18.4
Entering 3d pass	432	810	
Leaving 3d pass	443	830	
	11	20	4.3
Entering 4th pass	427	800	
Leaving 4th pass	430.3	806	
	3.3	6	1.3
Total rise	253.4	457	98.0

A contact process plant intended mainly for use with various concentrations of hydrogen sulfide (H_2S) as a feed material is known as a wet-gas plant, as shown in Figure 518. The wet-gas plant's combustion furnace is also used for burning sulfur or dissociating spent sulfuric acid. A common procedure for wet-gas plants located nea petroleum refineries is to burn simultaneously H_2S, molten sulfur, and spent sulfuric acid from the alkylation processes at the refineries. In some instances a plant of this type may produce sulfuric acid by using only H_2S or spent acid.

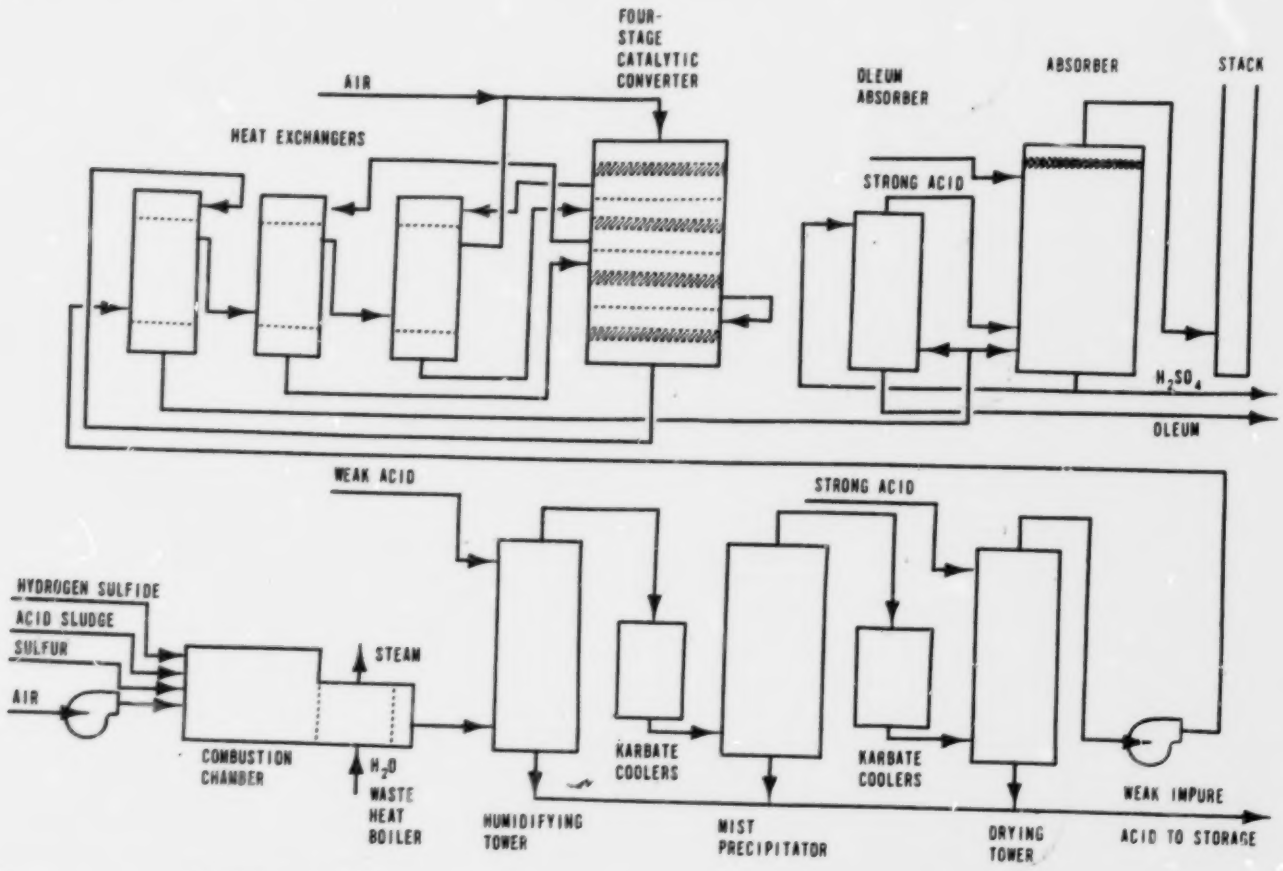


Figure 518. Flow diagram of a contact-type wet-gas sulfur plant.

In a wet-gas plant, the H_2S gas, saturated with water vapor, is charged to the combustion furnace along with atmospheric air. The SO_2 formed, together with the other combustion products, is then cooled and treated for mist removal. Gas may be cooled by a waste-heat boiler or by a quench tower followed by Karbate and updraft coolers. Mist formed is removed by an electrical precipitator. Moisture is removed from the SO_2 and airstream with concentrated sulfuric acid in a drying tower. A centrifugal blower takes suction on the drying tower and discharges the dried SO_2 and air to the converters. The balance of the wet-gas process is essentially the same as that of the previously discussed sulfur-burning process.

THE AIR POLLUTION PROBLEM

The only significant source of air contaminant discharge from a contact sulfuric acid plant is the tail gas discharge from the SO_3 absorber. While these tail gases consist primarily of innocuous nitrogen, oxygen, and some carbon dioxide, they also contain small concentrations of SO_2 and smaller amounts of SO_3 and sulfuric acid mist. Table 196 shows the SO_2 and SO_3 discharged from two wet-gas sulfuric plant absorbers.

Table 196. SULFUR TRIOXIDE AND SULFUR DIOXIDE EMISSIONS FROM TWO ABSORBERS IN CONTACT SULFURIC ACID PLANTS

	Outlet of absorber No. 1	Outlet of absorber No. 2
Gas flow rate, scfm	9,600	7,200
Sulfur trioxide, gr/scf	0.033	0.39
% by vol as SO_2	0.002	
lb/hr	2.73	2.4
Sulfur dioxide, gr/scf	2.63	2.45
% by vol	0.22	
lb/hr	216	151.2

A well-designed contact process sulfuric acid plant operates at 90 to 95 percent conversion of the sulfur feed into product sulfuric acid. Thus a 250-ton-per-day plant can discharge 1.25 to 2.5 tons of SO_2 and SO_3 per day. When present in sufficient concentration, SO_2 is irritating to throat and nasal passages and injurious to vegetation. SO_2 concentrations greater than 0.25 ppm cause injury to plants on long exposure. The permissible limit for humans for prolonged exposure is 10 ppm.

Tail gases that contain SO_3, owing to incomplete absorption in the absorber stack, hydrate and form a finely divided mist upon contact with atmospheric moisture. According to Fairlie (1936) the process temperature of gas going to the absorber should be on the lower side of a temperature range between 150° and 230°C. The optimum acid concentration in the absorbing tower is 98.5 percent. This concentration has the lowest SO_3 vapor pressure. The partial pressure of SO_3 increases if the absorbing acid is too strong, and SO_3 passes out with the tail gases. If a concentration of absorbing acid less than 98.5 percent is used, the beta phase of SO_3, which is less easily absorbed, is produced. A mist may also form when the process gases are cooled before final absorption, as in the manufacture of oleum.

Water-based mists can form as a result of the presence of water vapor in the process gases fed to the converter. This condition is often caused by poor performance of the drying tower. Efficient performance should result in a moisture loading of 5 milligrams or less per cubic foot. In sulfur-burning plants, mists may be formed from water resulting from the combustion of hydrocarbon impurities in the sulfur. Mists formed in the wet-purification systems of an acid sludge regeneration plant are not completely removed by electrostatic precipitation. The mists pass through the drying tower and are volatilized in the converter. The mist reforms, however, when the gases are cooled in the absorption tower. Water-based mists can also form from any steam or water leaks into the system.

The SO_3 mist presents the most difficult problem of air pollution control since it is generally of the smallest particle size. The particle size of these acid mists ranges from submicron to 10 microns and larger. Acid mist composed of particles of less than 10 microns in size is visible in the absorber tail gases if present in amounts greater than 1 milligram of sulfuric acid per cubic foot of gas. As the particle size decreases, the plume becomes more dense because of the greater light-scattering effect of the smaller particles. Maximum light scattering occurs when the particle size approximates the wave length of light. Thus, the predominant factor in the visibility of an acid plant's plume is particle size of the acid mists rather than the weight of mist discharged. Acid particles larger than 10 microns are probably present as a result of mechanical entrainment. These larger particles deposit readily on duct and stack walls and contribute little to the opacity of the plume.

AIR POLLUTION CONTROL EQUIPMENT

Sulfur Dioxide Removal

Water scrubbing of the SO_3 absorber tail gases can remove 50 to 75 percent of the SO_2 content. Scrubbing towers using 3-inch or larger stacked rings or redwood slats are often employed. On startups, when SO_2 concentrations are large, soda ash solution is usually used in place of straight water. Water scrubbing is feasible where disposal of the acidic waste water does not present a problem.

Tail gases may be scrubbed with soda ash solution to produce marketable sodium bisulfite. A cyclic process using sodium sulfite-bisulfite has also been reported. Steam regeneration costs in the cyclic process are, however, relatively high, and the capacity of the scrubbing solution is limited by the low solubility of sodium bisulfite. The dilute scrubber solution has, moreover, little economic value.

The most widely known process for removal of SO_2 from a gas stream is scrubbing with ammonia solution. It was developed by Consolidated Mining and Smelting Company and installed at its Trail, British Columbia, plant (Duecker and West, 1959). Single- and two-stage absorber systems reportedly reduce SO_2 concentrations in tail gases to 0.08 and 0.03 percent respectively. Two-stage systems are designed to handle SO_2 gas concentrations as great as 0.9 percent. Large SO_2 concentrations resulting from acid plant startups and upsets could be handled adequately by a system such as this.

Acid Mist Removal

Electrical precipitators

Electrical precipitators are widely used for removal of sulfuric acid mist from the cold SO_2 gas stream of wet-purification systems. The wet-lead-tube type is used extensively in this service.

Tube-type precipitators have also been used for treating tail gases from SO_3 absorber towers. More recently, however, two-stage, plate-type precipitators have been used successfully. One such unit, lead lined throughout to prevent corrosion, is designed to handle approximately 20,000 cfm tail gas from a 300-ton-per-day contact sulfuric acid plant. This wet-gas plant processes H_2S, sulfur, and spent alkylation acid. Dry gas containing SO_2, carbon dioxide, oxygen, nitrogen, and 5 to 10 milligrams of acid mist per cubic foot enters two inlet ducts to the precipitator. The gas flows upward through dis-

tribution tiles to the humidifying section. This section contains 5 feet of 3-inch single-spiral tile irrigated by 800 gpm weak sulfuric acid. The conditioned gas then flows to the ionizing section, which consists of about 75 grounded curtain electrodes and 100 electrode wire extensions.

Ionized gas then flows to the precipitator section where charged acid particles migrate to the collector plate electrodes. There are twelve 14- by 14-foot lead plates and 375 electrode wires. The negative wire voltage is 75,000. Acid migrating to the plates flows down through the precipitator and is collected in the humidifying section. The gas from the precipitator section flows to a 5-foot-diameter, lead-lined stack that discharges to the atmosphere 150 feet above grade.

The high-voltage electrode wires are suspended vertically by three sets of insulators. Horizontal motion is eliminated by four diagonally placed insulators, which are isolated from the gas stream by oil seals. All structural material in contact with the acid mist is lead clad. Electrical wires are stainless steel cores with lead cladding. Voltage is supplied from a generator with a maximum capacity of 30 kilovolt-amperes. A battery of silicon rectifiers supplies 75,000 volts of direct current to the electrode wires.

Table 197 shows the sulfur trioxide and sulfur dioxide emissions from the previously described two-stage electrical precipitator. The acid mist collection efficiency was only 93 percent. A mechanical rectifier was, however, supplying only 36,000 volts to the precipitator during this test. During normal operation, silicon rectifiers supply 75,000 volts to the electrode wires.

Packed-bed separators

Packed-bed separators employ sand, coke, or glass or metal fibers to intercept acid mist particles. The packing also causes the particles to coalesce by reason of high turbulence in the small spaces between packing. Moderate-sized particles of mist have been effectively removed in a 12-inch-deep bed of 1-inch Berl saddles with gas velocities of approximately 10 fps.

Glass fiber filters have not been very effective in mist removal because of a tendency on the part of the fiber to sag and mat. Nevertheless, experimental reports by Fairs (1958) on acid mist removal by silicone-treated glass wool are encouraging. A special fine-glass wool with a fiber diameter between 5 and 30 microns was used. The coarser fibers allowed adequate penetration of the bed by the mist particles to ensure a reasonable long life and provided sufficient support for the finer fibers in their trapping of the small acid mist particles.

The glass wool was treated by compressing it into a filter 2 inches thick to a density of 10 pounds per cubic foot. It was then placed in a sheet metal container and heated at 500°C for 1 hour. By this treatment, the stresses in the compressed fibers were relieved, and the fiber mass could be removed from the mold without losing shape or compression. The fibers were then treated with a solution of methyl chlorosilane.

Table 197. SULFUR TRIOXIDE AND SULFUR DIOXIDE EMISSIONS FROM A TWO-STAGE ELECTRICAL PRECIPITATOR SERVING A CONTACT SULFURIC ACID PLANT

	Inlet of precipitator	Outlet of precipitator
Gas flow rate, scfm	13,400	13,100
Gas temperature, °F	160	80
Average gas velocity, fps	36.5	20.6
Collection efficiency,[a] %		93
Moisture in gas, %	0.8	4.1
CO_2, % (stack conditions)	5.9	6
O_2, %(stack conditions)	9.6	8.4
CO, % (stack conditions)	0	0
N_2, % (stack conditions)	83.4	81.2
Sulfur trioxide,		
gr/scf	0.062	0.0048
lb/hr	7.1	0.54
% by volume	0.0042	0.00032
Sulfur dioxide,		
gr/scf	4.1	4.1
lb/hr	470	460
% by volume	0.345	0.345[b]

[a] A mechanical rectifier was supplying only 36,000 volts to the precipitator. During normal operation, silicon rectifiers supply 75,000 volts to the electrode wires. This should increase the acid mist collection efficiency appreciably.

[b] Rule 53.1 for "scavenger plants" is applicable to this plant rather than Rule 53a, which limits emissions of SO_2 to 0.2 percent by volume. This plant recovers SO_2 that would otherwise be emitted to the atmosphere.

The threshold concentration for mist visibility after scrubbing has been found experimentally by Fairs (1958) to be about 3.6×10^{-4} gram SO_3 per cubic foot. The discharge gases from the silicone-treated filter had an SO_3 concentration of 1.8 to 2.5×10^{-4} gram per cubic foot and no appreciable acid mist plume. A faint plume became perceptible at approximately weekly intervals but was eliminated by flushing the filter bed with water. The average tail gas-filtering rate for the treated filter was 15.6 cfm per square foot of filtering area for

a pressure drop of 9-1/2 to 10 inches water column. According to Fairs, the effective life of the silicone fiber should be at least 5,000 hours. Garnetted terylene was also used but was not as efficient as silicone-treated glass wool. It should, however, prove adequate for less stringent duties. Its life should be long since it does not require silicone pretreatment. The use of untreated glass wool fiber proved unsatisfactory in reducing the opacity of the acid mist plume.

Table 198 shows the SO_2 and acid mist emissions from the outlet of a typical silicone-treated, glass fiber mist eliminator. This control unit processes absorber discharge gas from a contact sulfuric acid plant. The acid mist collection efficiency for the fiber glass mist eliminator was 98.9 percent. A successful application of a mist eliminator using treated fiber (Figure 519) has been made by the Monsanto Chemical Company (Brink, 1959). The exact treatment given to the fiber is not available since it is the property of the inventor, J. A. Brink, Jr.

Table 198. EMISSIONS OF SULFUR DIOXIDE AND ACID MIST FROM THE OUTLET OF A SILICONE-TREATED, GLASS FIBER MIST ELIMINATOR SERVING A CONTACT SULFURIC ACID PLANT

	Mist eliminator inlet	Mist eliminator outlet	
	Acid mist	Acid mist	Sulfur dioxide
Concentration, gr/scf	0.30	0.035	1.50
Concentration, ppm	200	25	1,300
Weight, lb/hr	45	0.5	160
Collection efficiency, %		98.9	
Gas flow rate, scfm		14,000	
Avg gas velocity, fps		19	
Gas temperature, °F		160	

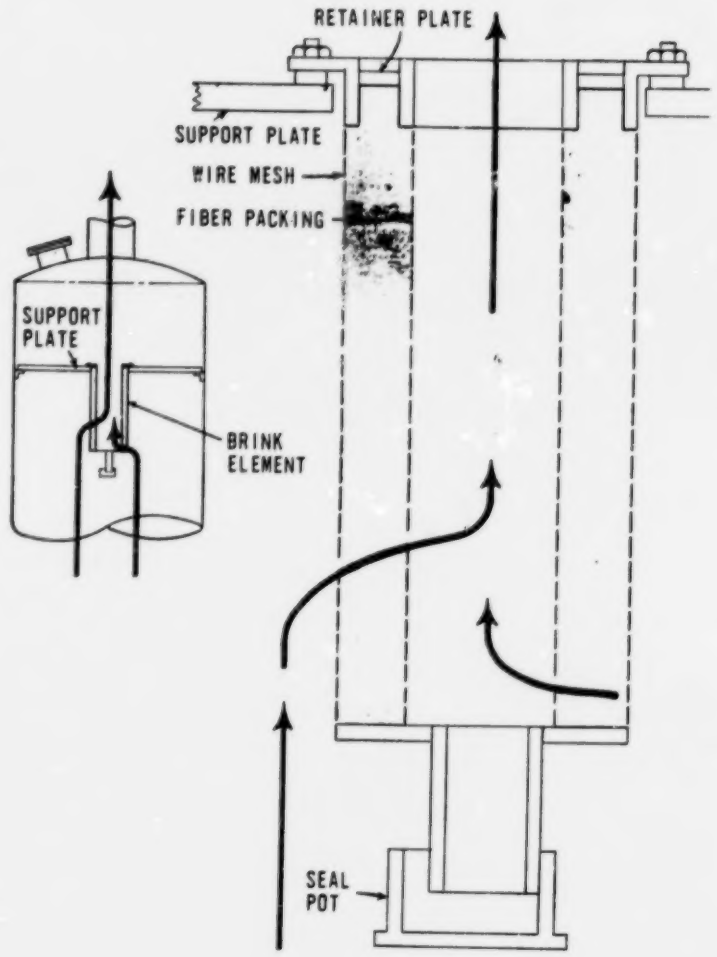


Figure 519. Brink fiber mist eliminator (Brink, 1959).

Wire mesh mist eliminators

Wire mesh mist eliminators are usually constructed in two stages. The lower stage of wire mesh may have a bulk density of about 14 pounds per cubic foot, while the upper stage is less dense. The two stages are separated by several feet in a vertical duct. The high-density lower stage acts as a coalescer. The re-entrained coalesced particles are removed in the upper stage. Typical gas velocities for these units range from 11 to 18 fps. The kinetic energy of the mist particle is apparently too low to promote coalescence at velocities less than 11 fps, and re-entrainment becomes a problem at velocities greater than 18 fps. The tail gas pressure drop through a wire mesh mist installation is approximately 3 inches water column.

Exit sulfuric acid mist loadings of less than 5 milligrams per cubic foot of gas are normally obtained from wire mesh units serving plants making 98 percent acid. No type of mechanical coalescer, however, has satisfactorily controlled acid mists from oleum-producing plants. Corrosion possibilities from concentrated sulfuric acid must be considered in selecting wire mesh material. The initial cost of wire mesh equipment is modest. The value of recovered sulfuric acid is usually sufficient to pay the first investment in 1 or 2 years (Duecker and West, 1959).

Ceramic filters

Porous ceramic filter tubes have proved successful in removing acid mist. The filter tubes are usually several feet in length and several inches in diameter with a wall thickness of about 3/8 inch.

The tubes are mounted in a horizontal tube sheet, with the tops open and the bottoms closed. The tail gases flow downward into the tubes and pass out through porous walls. Appreciably more filtering area is required for the ceramic filter than for the wire mesh type. The porous ceramic filter is composed of small particles of alumina or similar refractory material fused with a binder.

The maintenance costs for ceramic tubes is considerably higher than those for wire mesh filters because of tube breakage. Initial installation costs are also considerably higher than those for wire mesh. A pressure drop of 8 to 10 inches water column is required to effect mist removal equivalent to that of a wire mesh filter. Thus, operating costs would also be appreciable (Duecker and West, 1959).

Sonic agglomeration

The principle of sonic agglomeration is also used to remove acid particles from waste-gas streams. Sound waves cause smaller particles in an aerosol to vibrate and thereby coalesce into larger particles. Conventional cyclone separators can then be used for removal of these larger particles. One installation treating exit stack gases from a contact acid plant has been reported to remove 90 percent by weight of acid in the gas stream. The tail gases leaving the sonic collector contained 2 to 3 milligrams of 100 percent sulfuric acid mist per cubic foot. A nuisance factor must be taken into consideration, however, since some of the sound frequencies are in the audible range (Duecker and West, 1959).

Miscellaneous devices

Simple baffles and cyclone separators are not effective in collecting particles smaller than 5 microns in size. A considerable amount of the larger size acid mist particles may be removed; however, the visibility of the stack plume is not greatly affected, since the smallest particle size contributes most to visibility. Vane-type separators operate at relatively high gas velocities and thus make better use of the particles' kinetic energy. They have been found to be moderately effective for contact plants having wet-purification systems in reducing stack plume opacities (Duecker and West, 1959).

PHOSPHORIC ACID MANUFACTURING

During the past 20 years, the use of phosphorus-containing chemical fertilizers, phosphoric acid, and phosphate salts and derivatives has increased greatly. In addition to their very large use in fertilizers, phosphorus derivatives are widely used in food and medicine, and for treating water, plasticizing in the plastic and lacquer industries, flameproofing cloth and paper, refining petroleum, rustproofing metal, and for a large number of miscellaneous purposes. Most of the phosphate salts are produced for detergents in washing compounds.

With the exception of the fertilizer products, most phosphorus compounds are derived from orthophosphoric acid, produced by the oxidation of elemental phosphorus. At present, elemental phosphorus is manufactured on a large enough scale to be classed as a heavy chemical and is shipped in tank cars from the point of initial manufacture, where the raw materials are inexpensive, to distant plants for its conversion to phosphoric acid, phosphates, and other compounds.

PHOSPHORIC ACID PROCESS

Generally, phosphoric acid is made by burning phosphorus to form the pentoxide and reacting the pentoxide with water to form the acid. Specifically, liquid phosphorus (melting point 112°F) is pumped into a refractory-lined tower where it is burned to form phosphoric oxide, P_4O_{10}, which is equivalent algebraicly to two molecules of the theoretical pentoxide, P_2O_5, and is, therefore, commonly termed phosphorus pentoxide:

$$P_4 + 5O_2 \longrightarrow P_4O_{10}$$

An excess of air is provided to ensure complete oxidation so that no phosphorus trioxide (P_2O_3) or yellow phosphorus is coproduced. The reaction is exothermic, and considerable heat must be removed to reduce corrosion. Generally, water is sprayed into the hot gases to reduce their temperature before they enter the hydrating section.

Additional water is sprayed countercurrently to the gas stream, hydrating the phosphorus pentoxide to orthophosphoric acid and diluting the acid to about 75 to 85 percent:

$$P_4O_{10} + 6H_2O \longrightarrow 4H_3PO_4$$

The hot phosphoric acid discharges continuously into a tank, from which it is periodically removed for storage or purification. The tail gas from the hydrator is discharged to a final collector where most of the residual acid mist is removed before the tail gas is vented to the air. A general flow diagram for a phosphoric acid plant is shown in Figure 520.

The raw acid contains arsenic and other heavy metals. These impurities are precipitated as sulfides. A slight excess of hydrogen sulfide, sodium hydrosulfide, or sodium sulfide is added and the treated acid is filtered. The excess hydrogen sulfide is removed from the acid by air blowing.

The entire process is very corrosive, and special materials of construction are required. Stainless steel, carbon, and graphite are commonly used for this severe service.

Special facilities are required for handling elemental yellow phosphorus since it ignites spontaneously on contact with air at atmospheric temperatures and is highly toxic. Phosphorus is always shipped and stored under water to prevent combustion. The tank car of phosphorus is heated by steam coils to melt the water-covered phosphorus. Heated water at about 135°F is then pumped into the tank car and displaces the phosphorus, which flows into a storage tank. A similar system using hot displacement water is frequently used to feed phosphorus to the burning tower.

THE AIR POLLUTION PROBLEM

A number of air contaminants, such as phosphine, phosphorus pentoxide, hydrogen sulfide, and phosphoric acid mist, may be released by the phosphoric acid process.

Phosphine (PH_3), a very toxic gas, may be formed by the hydrolysis of metallic phosphides that exist as impurities in the phosphorus. When the tank car is opened, the phosphine usually ignites spontaneously but only momentarily.

Phosphorus pentoxide (P_4O_{10}), created when phosphorus is burned with excess air, forms an extremely dense fume. Our military forces take advantage of this property by using this compound to form smoke screens. The fumes are submicron in size and are 100 percent opaque. Except for this military use, phosphorus pentoxide is never released to the atmosphere unless phosphorus is accidentally spilled and exposed to air. Since handling elemental phosphorus is extremely hazardous, stringent safety precautions are mandatory, and phosphorus spills are very infrequent.

Hydrogen sulfide (H_2S) is released from the acid during treatment with NaHS to precipitate sulfides of antimony and arsenic and other heavy metals. Removal of these heavy metals is necessary for manufacture of food grade acid. H_2S is highly toxic and flammable. Health authorities recommend a maximum allowable concentration of this gas of 20 ppm for an 8-hour exposure. The odor threshold is 0.19 ppm (Gillespie and Johnstone, 1955). In practice, however, H_2S is blown from the treating tank and piped to the phosphorous-burning tower where it is burned to SO_2. Source test information indicates that the concentration of SO_2 in the gaseous effluent from the acid tower scrubber will not exceed 0.03 volume percent. Evolution of H_2S is also minimized by restricting the amount of NaHS in excess of that needed to precipitate arsenic and antimony and other heavy metals.

The manufacture of phosphoric acid cannot be accomplished in a practical way by burning phosphorus and bubbling the resultant products through either water or dilute phosphoric acid (Slaik and Turk, 1953). When water vapor comes into contact with a gas stream that contains a volatile anhydride, such as phosphorus pentoxide, an acid mist consisting of liquid particles of various sizes is formed almost instantly. An investigation (Brink, 1959) indicates that the particle size of the phosphoric acid aerosol is small, about 2 microns or less, and that it has a median diameter of 1.6 microns, with a range of 0.4 to 2.6 microns.

The tail gas discharged from the phosphoric acid plant is saturated with water vapor and produces a 100 percent opaque plume. The concentration of phosphoric acid in this plume may be kept small with a well-designed plant. This loss amounts to 0.2 percent or less of the phosphorus charged to the combustion chamber as phosphorus pentoxide.

HOODING AND VENTILATION REQUIREMENTS

All the reactions involved take place in closed vessels. The phosphorus-burning chamber and the hydrator vessel are kept under a slight negative pressure by the fan that handles the effluent gases, as shown in Figure 520. This is necessary to prevent loss of product as well as to prevent air pollution.

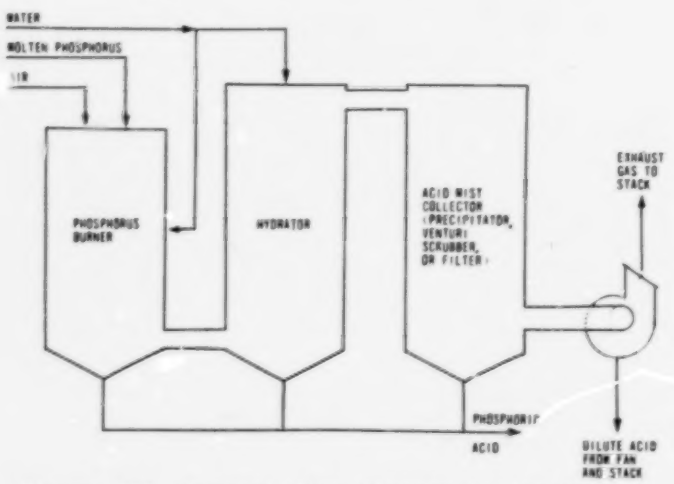


Figure 520. General flow diagram for phosphoric acid production.

The hydrogen sulfide generated during the acid purification treatment must be captured and collected, and sufficient ventilation must be provided to prevent an explosive concentration, for hydrogen sulfide has a lower explosive limit of 4.3 percent. The sulfiding agent must be carefully metered into the acid to prevent excessively rapid evolution of hydrogen sulfide.

AIR POLLUTION CONTROL EQUIPMENT

The hydrogen sulfide can be removed by chemical absorption or by combustion. Weak solutions of caustic soda or soda ash sprayed countercurrently to the gas stream react with the hydrogen sulfide and neutralize it:

$$Na_2CO_3 + H_2S \longrightarrow NaHCO_3 + NaHS$$

$$2NaOH + H_2S \longrightarrow Na_2S + 2H_2O$$

The hydrogen sulfide may also be oxidized in a suitable afterburner:

$$2H_2S + 3O_2 \longrightarrow 2H_2O + 2SO_2$$

The phosphoric acid mist in the tail gas is commonly removed by an electrical precipitator, a venturi scrubber, or a Brink fiber mist eliminator (Brink, 1959). All are very effective in this service.

The Tennessee Valley Authority has used electrical precipitators for many years to reduce the emission of phosphoric acid mist (Striplin, 1948). Severe corrosion has always been a problem with these precipitators. Published data (Slaik and Turk, 1953) indicate that the problem has been partially solved by reducing the tail gas temperature to 135° to 195°F. The acid discharged amounts to about 0.15 percent of the phosphorus pentoxide charged to the combustion chamber as phosphorus. The relatively low gas temperatures and consequently infrequent failure of the wires are given as the reason for the high mist recovery from the gas stream.

The TVA replaced one of the electrical precipitators with a venturi scrubber in 1954. The venturi scrubber is constructed of stainless steel and is 14 feet 6 inches high, with a 30-inch-diameter inlet and outlet and a 11-1/2-inch-diameter throat (Barber, 1958). The scrubber is followed by a centrifugal entrainment separator. Stack analyses of emissions from this production unit are summarized in Table 199.

Table 199. STACK ANALYSES OF EMISSIONS FROM A PHOSPHORIC ACID PLANT WITH A VENTURI SCRUBBER

Phosphorus burning rate, lb/hr	2,650
Temperature, °F	
Vaporizer outlet	1,650
Burner outlet	880
Venturi scrubber outlet	195
Stack gas	175
Pressure drop, in. WC	
Across venturi scrubber	25.2
Across entrainment separator	1.9
Emissions as % of phosphorous burned	0.2

In 1962, the TVA constructed a stainless steel phosphoric acid unit that has an adjustable venturi scrubber, followed by a packed scrubber, and a wire mesh mist eliminator. When the venturi scrubber is adjusted to give a pressure drop of 37 inches of water column or higher, losses of P_2O_5 from the unit amount to only about 5 pounds per hour at phosphorus-burning rates up to 6,000 pounds per hour.

Considerable research and development work by the TVA demonstrated that good recovery of phosphoric acid mist could be achieved by introducing water vapor into the hot gases from the combustion of phosphorus, passing the mixture through a packed tower, and condensing it (Slaik and Turk, 1953).

A large-scale plant using a Raschig ring-packed tower followed by three gas coolers was built. Overall phosphorus pentoxide recovery exceeded 99.9 percent, but the process was eventually abandoned because of the excessive rate of corrosion of the gas coolers.

This same process, with a second packed scrubber or glass fiber-packed filter unit for acid mist removal replacing the gas cooler, is used by a number of phosphoric acid producers throughout the country. These plants routinely operate with phosphorus pentoxide recovery efficiencies in excess of 99.8 percent. A visible phosphoric acid plume still remains, though the phosphorus content has been reduced to less than 0.1 grain per scf. A plant such as this is in operation in Los Angeles County and is shown in Figure 521. The plume contains a large percentage of water vapor and does not violate local air pollution prohibitions. Stack analyses of emissions from this plant are shown in Table 200.

The packed scrubber must be thoroughly and uniformly wetted with either water or weak acid and must have uniform gas distribution to achieve high

Table 200. STACK ANALYSES OF EMISSIONS FROM A PHOSPHORIC ACID PLANT WITH TWO RASCHIG RING-PACKED SCRUBBERS

	Report series No.	
	C-167 A	C-167 B
Phosphorus burning rate, lb/hr	1,875	895
Gas rate, stack outlet, scfm	12,200	3,420
Gas temperature, stack outlet, °F	175	162
Diameter of first packed scrubber, ft	8.5	8.5
Height of first scrubber's Raschig ring packing, ft	12	12
Diameter of final packed scrubber, ft	20	20
Height of final scrubber's Raschig ring packing, ft	3	3
Final scrubber's superficial velocity, fpm	47	13
P_2O_5 emitted, gr/scf	0.095	0.108
P_2O_5 emitted, lb/hr	9.9	3.2
Emissions as % of phosphorus burned	0.23	0.16

collection efficiency. Good gas distribution is also mandatory for glass fiber filter units, and a superficial gas velocity of less than 100 fpm is recommended.

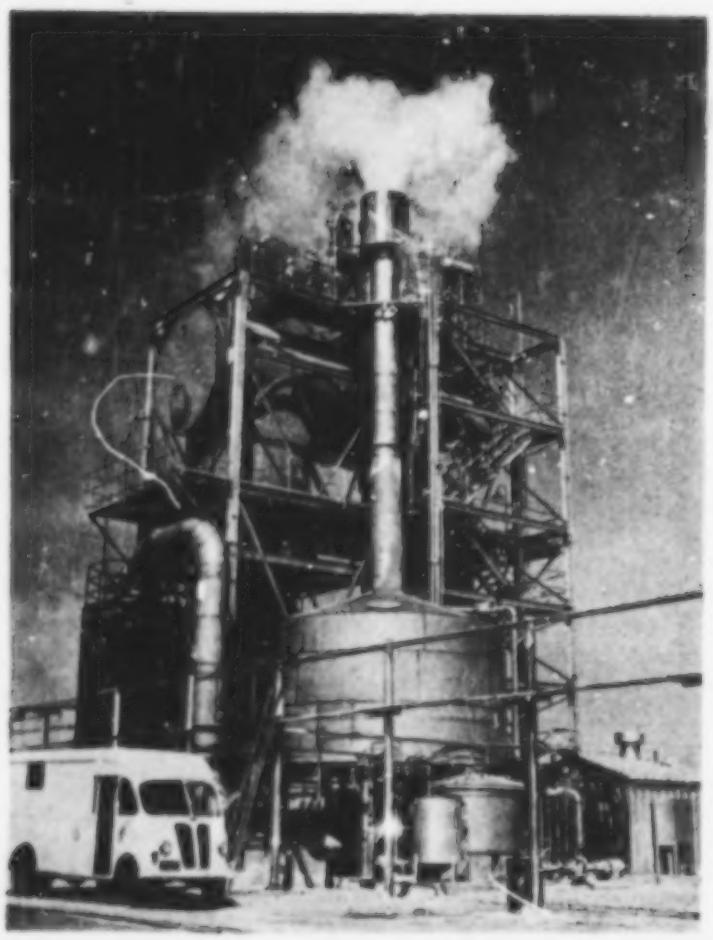


Figure 521. Phosphoric acid plant with a Raschig ring-packed scrubber.

The Brink (1959) fiber mist eliminator is a relatively new type of collector that has been used successfully on sulfuric acid mist, oleum, phosphoric acid, ammonium chloride fume, and various organics. Collectors of this type have been discussed in the preceding section of this chapter.

At one plant owned by Monsanto Chemical Company, the stack plume was very persistent and visible. Thirty milligrams of fine sulfuric acid mists per standard cubic foot and 80 to 200 milligrams of phosphoric acid particles per standard cubic foot were emitted from the stack. To correct the situation, a gas absorption apparatus followed by a fiber mist collector was installed. Collection efficiencies of 99 percent on particles less than 3 microns in diameter and of 100 percent on larger particles were achieved. The stack plume, which consists of 15 percent water vapor, disappears within 40 to 50 feet of the stack on dry days and within 150 feet on wet days. No maintenance problems or changes in pressure drop through the apparatus have been encountered.

PAINT-BAKING OVENS

Although bake ovens have extensive industrial applications, this section is limited to those used to dry or harden surface coatings concurrently with the removal of organic solvents by evaporation. Moreover, the word paint is used throughout this section as a general term for any of the many and varied types of surface coatings, for example, inks, varnishes, paints, enamels, lacquers, shellacs, and resins.

Paint baking causes not only the evaporation of the organic solvents used as diluents and thinners but also the drying and hardening of a surface coating. The essential requirement in paint baking is that the paint be exposed to the proper de-

gree and amount of heat, but there are other requirements, too, as follows:

1. Within the oven, the atmosphere resulting from the vaporization of organic solvents from the paint must be maintained below the lower explosive limit (LEL).

2. When the doors are open and employees are loading or unloading the oven, the atmosphere within the oven must be kept well below the toxic level.

3. The atmosphere in which the painted surface is baked must, in some cases but not all, be kept free from the products of incomplete combustion of the oil or gas used for firing.

4. The atmosphere within the oven must be free from dust.

5. The nuisance and air pollution potentials of emissions from the oven to the cutside atmosphere must be evaluated.

BAKE OVEN EQUIPMENT

A bake oven is a heated enclosure used industrially to dry and bake materials at elevated temperatures. In paint drying and baking, these temperatures may range from 100° to 600°F. The typical construction of a bake oven consists of a framework of heavy structural steel that supports an inner and outer shell of heavy-gage steel sheet metal. The space between the inner and outer shell is filled with insulation that should be supported to prevent separation and settling. Allowance should be made for expansion and contraction due to temperature changes, and the amount of steel in contact with both hot and cold sides should be kept to a minimum to reduce heat loss. Heavy, insulated double doors with approved explosion-type catches are characteristic of industrial bake ovens.

In some ovens, the products of combustion enter and come into direct contact with the work in process; in other ovens, the heating is indirect, and the products of combustion do not enter the oven nor do they at any time come into contact with the work in process. The source of heat may be gas, electricity, oil, steam, or infrared lamps, whichever is available and appropriate to the process. In all bake ovens, accurate, dependable temperature control and uniform heating are requisites. All three methods of heat transfer are used in any paint bake oven. The heat radiates from the hot oven walls. The movement of the heated air by means of circulating fans applies heat by mechanical convection. The interior of the paint film is heated by conduction through the article upon which the paint has been applied as well as by internal conduction through the paint itself.

An exhaust fan should be provided for all but the smaller ovens. The exhaust duct's intake openings should be located in the area of the greatest concentration of vapors. In general, the organic vapors from the volatile organic solvents customarily used in paints are heavier than air. For this reason, bottom ventilation of a paint-baking oven is indicated. The products of combustion from the burning of fuel are, however, lighter than air and should, therefore, be vented from the top. The products of combustion from indirectly gas- or oil-fired air heaters are preferably exhausted by a separate draft fan not connected to the oven's ventilation.

In addition, every properly designed bake oven has a number of automatic safety features to meet the recommendations of insurance inspection services, but these features will not be discussed here since they can be learned from the National Fire Protection Association (1963).

Batch process paint-baking ovens have an insulated chamber, some form of air circulation, a combustion system, a heat exchanger, a variety of safety controls, fresh air filters, and either a natural-draft or an induced-draft exhaust system (Figure 522). The painted

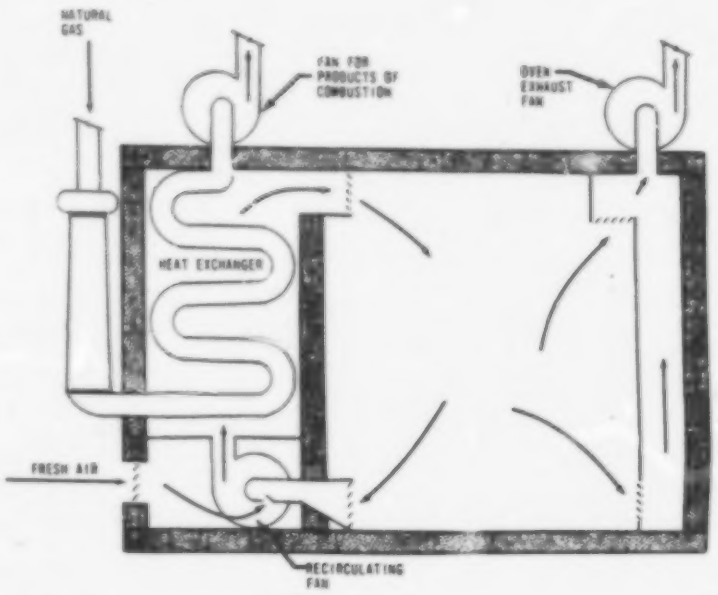


Figure 522. An indirectly heated, gas-fired, recirculating, batch-type paint-baking oven.

products to be baked may rest on permament racks or hooks inside the oven or may be placed on trucks that can be moved in and out of the oven for loading or unloading. Batch paint-baking ovens offer the advantage of low investment and are completely adequate for many jobs. Because the items to be baked are all put into the oven at one time, the organic solvents do not evaporate at a constant rate. Since a peak evaporation rate is reached within a few minutes after loading, all the organic solvents will have evaporated long before the work load is removed from the oven.

For large-volume production, continuous-type paint-baking ovens are usually used. These are high-production machines that permit a precise control of baking conditions. They can be designed and built in units to meet any production requirements. A continuous bake oven, as shown in Figure 523, consists principally of an insulated cabinet with positively controlled circulation of heated air, combustion systems, safety controls, fresh air filters, induced-draft exhaust, and a moving conveyor or belt by which the painted product is carried into, through, and out of the oven. Automatic control devices maintain any desired baking conditions. Because the workload is introduced into a continuous oven in a steady stream by means of an endless belt or conveyor, the evaporation of organic solvents approaches a constant rate.

THE AIR POLLUTION PROBLEM

The air pollutants emitted from paint-baking ovens are as follows:

1. Smoke and products of incomplete combustion arise from the improper operation of a gas- or oil-fired combustion system used for heating the oven.

2. Organic-solvent vapors arise from the evaporation of the thinners and diluents used in the surface coatings. A classification of the organic solvents used in surface-coating formulations, giving general formulae and examples, is shown in Tables 201 and 202. The composition of the organic-solvent vapors emitted from a paint-baking oven might be expected to have the same composition as that of the organic solvents used in the formulation and thinning of the surface coating, but they do not. Partially oxidized and polymerized compounds are produced at bake oven temperatures. When effluent from paint-baking ovens is irradiated in the presence of NO, it can produce eye irritation as severe as that produced by automobile exhaust.

3. The aerosols resulting from the partial oxidation and polymerization of the organic solvents and resins used in the paint formulation are obnoxious from the stand-

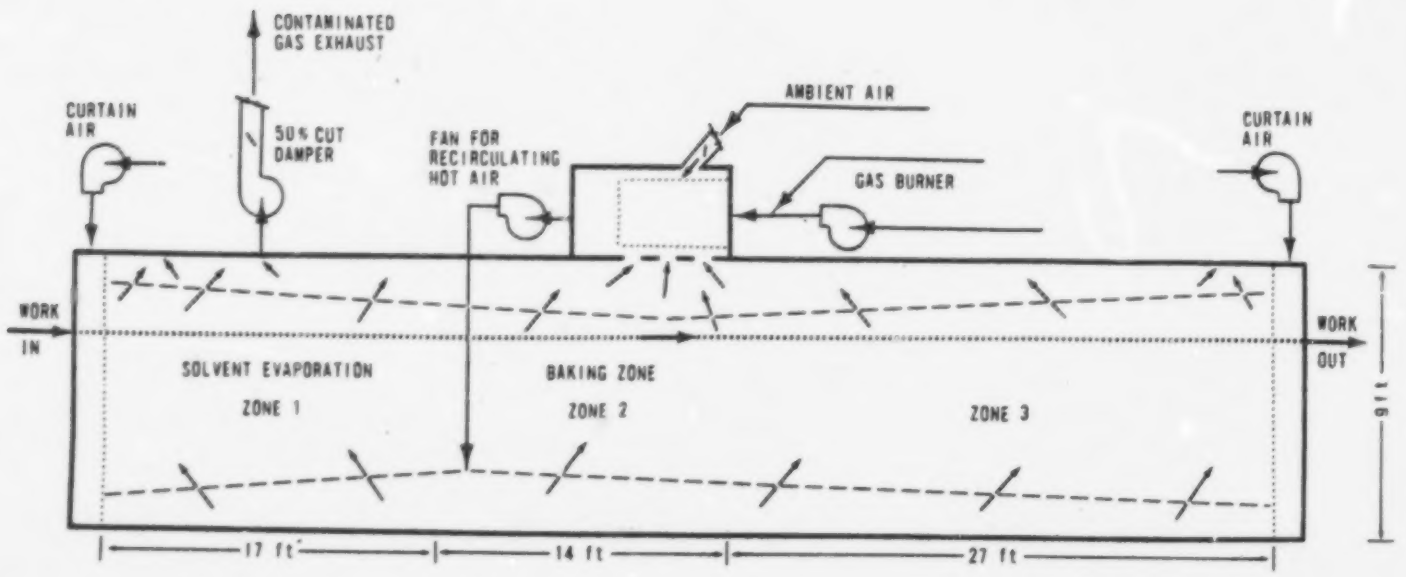


Figure 523. A direct-heated, gas-fired, recirculating, continuous paint-baking oven, as used in Example 41 (Zone 1 is 4 ft wide; zone 2, 5 ft 4 in. wide; zone 3, 4 ft wide.).

Table 201. CLASSIFICATION OF ORGANIC SOLVENTS USED IN SURFACE COATING (Lunche et al., 1957)

Class name	General formula[a]	Examples
Aliphatic hydrocarbons	R-H	Hexane, Stoddard solvent, naphtha, mineral spirits
Aromatic hydrocarbons	Φ-H	Benzene, toluene, xylene
Ketones	$R-\overset{O}{\overset{\|\|}{C}}-R'$	Methyl, ethyl ketone, acetone, methyl isobutyl ketone
Alcohols (and glycols)	R-OH	Methanol, isopropanol, sec-butonol, ethanol
Ethers	R-O-R'	Ethyl ether
Esters	$R-\overset{O}{\overset{\|\|}{C}}-O-R'$	Ethyl acetate, butyl acetate, n-butyl acetate
Miscellaneous[b]		Turpentine, carbon disulfide, nitromethane

[a]R or R' = any straight- or branched-chain hydrocarbon radical.
Φ = any benzene ring-type hydrocarbon radical.
O = oxygen atom.
C = carbon atom.
H = hydrogen atom.
[b]Aldehydes, terpenes, sulfur compounds, nitrogen compounds, mixtures.

points of odor nuisance. Moreover, these emissions are extremely irritating to eyes even without irradiation.

Table 202. CLASSIFICATION OF ORGANIC SOLVENTS AND EXAMPLES (Lunche et al., 1957)

Mineral spirits and terpenes	Alcohols and glycol ethers
Aliphatic hydrocarbons and mixtures	Methanol
Turpentine	Ethanol
Dipentene	Isopropyl alcohol
Hexane	N-butanols
Cyclohexane	Sec-butanols
Naphtha	Cellosolves (not including esters)
Aromatic hydrocarbons	"Carbitol"
Benzol	Methyl isobutyl carbinol
Toluol	Mixed alcohols
Xylols	**Chlorinated hydrocarbons**
Aromatic mixtures	Trichloroethylene
Ketones	Perchloroethylene
Acetone	Mono-chlorobenzene
Methyl ethyl ketone	Di-chlorobenzene
Diisobutyl ketone	Ethylene dichloride
Cyclohexanone	Carbon tetrachloride
Ethyl amyl ketone	Chloroform
Diacetone alcohol	Chloroethene
Isophorone	Mixed chlorinated solvents
Methyl isobutyl ketone	**Others**
Mesityl oxide	Carbonbisulfide
Mixed ketones	Dimethyl formamide
Esters	Ethyl ether
Ethyl acetate	Nitro methane
Amyl acetate	Nitro benzene
N-butyl acetate	
Cellosolve acetate	
N. isopropyl acetate	
Methyl amyl acetate	
Mixed esters	

HOODING AND VENTILATION REQUIREMENTS

Fire underwriters' standards demand that sufficient fresh air be adequately mixed with the organic-solvent vapors inside the oven so that the concentrations of flammable vapor in all parts of the oven are safely less than the lower explosive limit (LEL) at all times. The LEL of gas in air is the minimum volume at which it will burn, expressed in percent by volume. As an approximate rule, the vapors produced by 1 gallon of most organic solvents, when diffused in 2,500 cubic feet of air at 70°F, form the leanest mixture that still explodes or flashes in the presence of a flame or spark. A factor of safety four times the LEL is customarily provided. For each gallon of organic solvent evaporated in a paint-baking oven, therefore, at least 10,000 cubic feet of fresh air (computed at 70°F) must be supplied to the oven. Ovens vented to solvent recovery systems, however, are exempted from this requirement.

Additional requirements of the fire underwriters' standards are:

1. The exhaust duct openings shall be located in the area of the greatest concentration of vapors.

2. The oven must be mechanically ventilated with power-driven fans.

3. Each oven shall have its own individual exhaust system (there are some exceptions for very small ovens), which is, moreover, not connected with any exhaust system used to vent the products of combustion from indirectly gas- or oil-fired heaters.

4. The fresh air supplied shall be thoroughly circulated to all parts of the oven.

5. Dampers must be so designed that, even when fully closed, they permit the entire volume of fresh air needed for meeting the demands of safe ventilation to pass through the oven.

6. A volume of air equal to that of the fresh outside air supplied must be exhausted from the oven in order to keep the system in balance.

7. If a shutdown occurs during which vapors could accumulate in the oven, the oven shall be purged for a length of time sufficient to permit four complete oven volume air changes.

The designer of air pollution control equipment must be concerned with the fire underwriters' standards for paint-baking oven installations. It is pointless to design a control system for ovens that does not meet the LEL standards of the fire underwriters. The large volumes of air used to dilute the organic-solvent vapors in these ovens have a major effect on the design and operation of the air pollution control equipment.

AIR POLLUTION CONTROL EQUIPMENT

Smoke and products of incomplete combustion can be eliminated as a source of air pollution by proper selection of burners and fuels along with observance of correct operating procedures (see Chapter 9, Combustion Equipment).

The air pollution problem can be diminished by decreasing the operating temperature inside the paint-baking oven. Eye irritation has repeatedly been observed from oven emissions when the operating temperature of the oven was above 375°F. Markedly less eye irritation was noted when the operating temperature of the oven was kept below this temperature. In one case, the reduction of excessive oven temperature resulted in an improvement of product quality with no loss of production. This indicates that there undoubtedly are optimum temperature and time relationships in bake oven operations that could be exploited in the interests of reducing air pollution.

The use of water-based surface coatings offer another possible opportunity to reduce organic-solvent emissions from paint-baking ovens.

Organic-solvent vapors, odors, and aerosols emitted from paint-baking ovens can best be controlled by being vented to direct-fired vapor combustion devices operated at temperatures of 1,400°F or higher. Catalytic afterburners have not proved as satisfactory as the direct-fired afterburners for this use. Tables 203 and 204 show efficiencies of direct-flame afterburners and catalytic afterburners, respectively. In some cases, as shown in Table 204, the organic emissions from a paint-baking oven have been more offensive and irritating to eyes after passing through a catalytic afterburner than they were on entering the afterburner. This is true even at temperatures of 900° to 1,000°F, considered to be high for catalytic units.

COST OF DIRECT-FLAME AFTERBURNERS

The cost of installing a direct-flame afterburner for the control of organic-solvent vapor emissions from a paint-baking oven depends upon the capacity of the afterburner, the amount of instrumentation required, and the degree of corrosion resistance needed. The costs listed in Table 205 are for complete installations only and include the costs of the afterburner, the foundation work, the ductwork, the utilities, (installed and connected), complete instrumentation, the furnace and burner controls, the fan, the stack, and also a test involving all necessary adjustements.

Illustrative Problem

Example 41

Given:

A continuous oven (similar to that shown in Figure 523) is to be used to bake steel parts of various shapes for metal furniture. The parts to be baked enter the oven at one end on an overhead conveyor at 3 to 7 fpm conveyor speed and leave at the other end. The parts are to be baked at 375°F. They are coated with enamel mixed with thinner in the proportion of 4 gallons of enamel to 1 gallon of thinner. The total consumption of thinned enamel does not exceed 40 gallons per 8-hour day.

The enamel weighs 9.2 pounds per gallon and 49 percent is nonvolatiles (see Table D10 in Appendix D). The thinner weighs 7 pounds per gallon.

A direct-fired heater and a 5-hp blower provide 4,800 cfm heated air. This air circulates through the oven and the direct-fired heater where a portion of the fumes from the baking

Table 203. EFFICIENCY OF DIRECT-FLAME AFTERBURNERS IN THE CONTROL OF CONTAMINANTS EMITTED FROM PAINT-BAKING OVENS

Source test No.	Type of coating applied	Class of solvent used[a]	Afterburner temp, °F	Reduction obtained, %			
				Odor[b]	Particulates[c]	Combustible gases[d]	Aldehydes[e]
C-722	Vinyl	Ketones, aromatics	1,100	15	58	-	1.3 x[f]
			1,200	40	70	-	18
			1,400	98.8	87	-	57
C-722	Enamel (sanitary)	Mineral spirits, aromatics	1,100	2.5 x[f]	1.2 x[f]	-	1.6 x[f]
			1,200	42	1.5	-	1.1 x[f]
			1,400	94.2	74	-	81
C-767	Vinyl No. 53	Aromatics, ketones	1,100	0	-	1.2 x[f]	-
			1,200	90	-	1.5	-
			1,300	86	-	34	-
			1,400	98.3	-	95	-
C-776	Varnish No. 127 (oleoresin)	Aromatics, aliphatics, mineral spirits	1,100	-	-	29	-
			1,200	-	-	38	-
			1,300	-	-	39	-
			1,400	-	-	69	-
C-795	Varnish (alkyd resin)	Alcohols, aromatics, aliphatics	1,100	1.7 x[f]	-	41	-
			1,200	40	-	48	-
			1,300	98.3	-	75	-
			1,400	98.6	-	95	-
C-820	Varnish (alkyd amine)	Mineral spirits, aromatics	1,200	-	-	60	-
			1,300	-	-	79	-
			1,400	-	-	92	-

[a]Refer to Table 202.
[b]Odor concentrations were determined by the Los Angeles County Air Pollution Control District's Standard Method (see Appendix C).
[c]Particulate matter was determined by the APCD Source Test Method.
[d]Combustible gases were determined by the CCIR Method.
[e]Aldehydes were determined by the APCD 5-46 Method.
[f]This notation represents an increase in concentration. The number is a multiplying factor to be applied to the afterburner's inlet concentration.

process is burned on each air change. Since the inside volume of the oven is 2,252 cubic feet, there are 2.13 air changes per minute in the oven (4,800 cfm/2,252 cf = 2.13).

Two 3-hp blowers provide air seals, one at each end of the oven. A 3/4-hp exhauster removes a portion of the contaminated air and provides one fresh air change in the oven each 1.5 minutes in order to remove the fumes arising from the paint-baking process. The burner supplied with this oven is rated at 1,200,000 Btu per hour. Assume the overall heat transfer coefficient for this oven is 0.66 Btu per hour per square foot per °F.

Problem:

Determine the design features of an air pollution control system incorporating an afterburner to serve this oven.

Solution:

1. Total weight of solvent emitted per day:

   The maximum daily usage of thinned enamel is 40 gallons, and this is a blend of 4 gallons of unthinned enamel plus 1 gallon of thinner. There are, therefore, (40/5)(4) = 32 gallons of unthinned enamel used per day plus (40/5)(1) = 8 gallons of thinner per day.

   The volatiles in the unthinned enamel are (32)(9.2)(1.00-0.49) = 150 pounds, and the volatiles in the thinner are (8)(7) = 56 pounds per day.

   150 + 56 = 206 lb solvent emitted per day

Table 204. EFFICIENCY OF CATALYTIC AFTERBURNERS IN THE CONTROL OF CONTAMINANTS EMITTED FROM PAINT-BAKING OVENS

Source test No.	Type of coating applied	Class of solvent used[a]	Afterburner temp, °F	Reduction obtained, %			
				Odor[b]	Particulates[c]	Combustible gases[d]	Aldehydes[e]
C-?39	C-Enamel	Aromatics, aliphatics	740	-	1.1 x[f]	-	100
C-258	Phenolic	Aromatics, aliphatics, alcohols, ketones	760 760	- - - -	1.1 x[f] 1.4 x[f]	- -	59 33
C-276	Varnish (alkyd resin)	Alcohols, aromatics, aliphatics	700 800 900	- - -	3.5 x[f] 4.3 x[f] 65	- - -	- - -
C-374	Vinyl (No. 52 Al.)	Aromatics, ketones	800 925 1,200	- - -	41 50 71	- - -	33 1.3 x[f] 1.25 x[f]
C-374	Varnish	Aromatics, aliphatics, alcohols	800 925 1,050	- - -	25 21 60	- - -	38 1.4 x[f] 29
C-374	Vinyl (No. 53 Gold)	Aromatics, ketones	970 1,060	- -	63 60	- -	1.8 x[f] 1.8 x[f]
C-374	Enamel (No. 127)	Aromatics, aliphatics, mineral spirits	800 925 1,050	- - -	11 0 13	- - -	0 50 33
C-375	Vinyl (No. 52 Al.)	Aromatics, ketones	700 800 900	- - -	33 57 62	- - -	2.7 x[f] 3.2 x[f] 2.2 x[f]
C-375	Enamel (No. 127) oleoresin	Aromatics, aliphatics, mineral spirits	700 800 900	- - -	15 1.9 x[f] 1.4 x[f]	- - -	89 75 33
C-375	Varnish (No. 10-304)	Aromatics, aliphatics, mineral spirits	700 800 900	- - -	1.1 x[f] 46 39	- - -	70 24 1.4 x[f]
C-375	Vinyl (No. 53 Gold)	Aromatics, ketones	700 800 900	- - -	61 58 66	- - -	13 1.4 x[f] 1.3 x[f]
C-391	Vinyl	Aromatics, mineral spirits, ketones	950 950	- -	55 48	- -	7.5 x[f] 10 x[f]
C-410	Vinyl	Aromatics, mineral spirits, ketones	1,010	-	79	-	4.7 x[f]
C-579	Varnish (No. 2201) (alkyd amine)	Mineral spirits, aromatics	700 800 900 1,000	1.2 x[f] 1.2 x[f] 1.2 x[f] 1.2 x[f]	- - - -	77 85 82 89	- - - -
O-12-62	Enamel (No. 1106 B) oleoresin		850 950 1,000	2.9 x[f] 1.4 x[f] 36	- - -	- - -	- - -

[a]Refer to Table 202.
[b]Odor concentrations were determined by the Los Angeles County Air Pollution Control District's Standard Method (see Appendix C).
[c]Particulate matter was determined by the APCD Source Test Method.
[d]Combustible gases were determined by the CCIR Method.
[e]Aldehydes were determined by the APCD Method 5-46.
[f]This notation represents an increase in concentration. The number is a multiplying factor to be applied to the afterburner's inlet concentration.

Table 205. COST OF DIRECT-FLAME AFTERBURNER, $/scfm CONTAMINATED GAS TO BE INCINERATED

Volume of contaminated gases, scfm	Cost,[a] $/scfm
500	15
1,000	10
2,000	7
4,000	6

[a] These costs are for complete installations and include: the afterburner, the foundation work, the ductwork, the utilities installed, complete instrumentation, the furnace and burner controls, the fan, the stack, and also a test involving all necessary adjustments.

2. Quantity of solvent emitted from the oven per day:

Of the 206 pounds of solvent emitted to the atmosphere per day, 60 percent is chargeable to the spray coating operation, and 40 percent to the paint-baking oven (see Table 206). The selection of the percent loss to be charged to the oven depends upon the time that elapses from the application of surface coating until the item enters the oven, the item being coated, the type surface coating applied, the type and amount of thinner used, the ambient temperature, and the effect of stray air currents.

$\frac{(206)(0.40)}{7}$ = 11.8 gal solvent emitted per day

3. Volume of contaminated air exhausted from the paint-baking oven per 8-hour work day:

$\frac{2,252\ ft^3}{1.5\ min}$ = 1,500 cfm contaminated air at 375°F exhausted from the paint-baking oven

$(1,500)(60)(8)$ = 720,000 ft^3/day of contaminated air exhausted from the paint-baking oven

4. Volume of contaminated air exhausted per gallon of solvent emitted:

$\frac{720,000}{11.8}$ = 61,017 ft^3 air/gallon solvent

5. Safety factor of oven versus that required by the fire underwriters' standard:

The safety factor required by the underwriters is 4 x LEL (in order to prevent the vapor concentration from exceeding 25% LEL). Since the solvents used as diluents in this enamel are not specified, assume the thinner to be a mixture of xylol and mineral spirits. At 70°F, the LEL of xylol is 1.0, and that of mineral spirits is 0.77 (refer to Table 207). Whenever multicomponent solvents are used, the individual solvent chosen should be that whose data result in the largest volume of air required. In this case it will be mineral spirits. The volume of air at 70°F that is rendered barely explosive per gallon of solvent is given in column J, Table 207. It can also be computed, if necessary, by the following formula:

$$\frac{(8.33\ (G)(100\text{-}LEL)}{(0.075)(\rho_s)(LEL)} = \text{volume in } ft^3 \text{ at } 70°F$$

Table 206. SOLVENT LOSS, % TO BE CHARGED TO A PAINT-BAKING OVEN OPERATED IN CONJUNCTION WITH VARIOUS METHODS OF APPLYING THE SURFACE COATING

Method of applying the surface coating	Loss[a] charged to the oven, %
Spray coating	10 to 30
Spray coating large flat surfaces	20 to 40
Dip coating	30 to 60
Flow coating	30 to 60
Roller coating	50 to 80

[a] The selection of % of loss depends upon the time that elapses from the application of the surface coating until the item enters the oven, the item being coated, the type of surface coating being applied, the type and amount of thinner used, the ambient temperature, and the effect of stray air currents.

8.33 = weight in pounds of 1 gallon of water at 70°F

G = specific gravity of the solvent (water = 1.0)

LEL = lower explosive limit of the solvent

0.075 = weight, lb of 1 ft^3 of air at 70°F and 29.9 inches of mercury pressure

ρ_s = vapor density of the solvent (air = 1.0).

For mineral spirits, therefore:

$\frac{(8.33)(0.8)(100\text{-}0.8)}{(0.075)(3.9)(0.8)}$ = 2,825 ft^3/gal at 70°F

Table 207. PROPERTIES OF COMMONLY USED FLAMMABLE LIQUIDS[a] (National Fire Protection Association, 1963)

	A Molecular wt[b]	B Flash point, °F	C Ign temp, °F	D Explosive limits, % by volume Lower	D Upper	E Specif gravity (Water=1)	F Vapor density (Air=1)	G Boiling point, °F	H Lb/gal	I Vapor, ft³ per gal liquid	I per lb liquid	J Approximate ft³ of air rendered barely explosive per gal of solvent[c,d]
Acetone	58	0	1,000	2.6	12.8	0.8	2.00	134	6.66	44.4	6.66	1,663
Amyl acetate n	130	77	714	1.1	7.5	0.9	4.5	300	7.50	22.2	2.96	1,976
Amyl acetate iso	88	77	715	1.0	7.5	0.9	4.5	290	7.50	22.2	2.96	2,198
Amyl alcohol n	88	91	572	at 212°F 1.2	10.0 at 212°F	0.8	3.0	280	6.66	29.6	4.44	2,437
Benzine (petroleum ether)	....	< 0	550	1.1	5.9	0.6	2.5	95 to 140	5.00	26.6	5.32	2,392
Benzol (benzene)	78	12	1,044	1.4	7.1	0.9	2.8	176	7.50	35.7	4.76	2,503
Butyl acetate n	116	72	790	at 212°F 1.7	7.6	0.9	4.00	260	7.50	24.9	3.33	1,435
Butyl alcohol n	74	84	650	1.4	11.2	0.8	2.6	243	6.66	34.2	5.15	2,408
Butyl alcohol--iso	74	82	800	1.7	10.9	0.8	2.6	225	6.66	34.2	5.15	1,978
Butyl cellosolve	118	141	472	at 212°F	at 212°F	0.902	4.07	340	7.51[e]	24.6	3.26	....
Butyl propionate	130	90	800	....	....	0.9	4.5	295	7.5	22.3	2.98	....
Camphor	152	150	871	....	....	1.0	5.2	408	8.33	21.4	2.57	....
Carbon disulfide	76	-22	212	1.3	44	1.3	2.6	115	10.83	55.5	5.13	4,214
Cellosolve (ethyl cellosolve)	90	104	460	2.6	15.7	0.931	3.10	275	7.75	33.3	4.32	1,248
Cellosolve acetate	132	124	715	1.7	....	0.975	4.72	313	8.13	23.0	2.82	1,327
Chlorobenzene--mono	113	90	1,180	1.3	7.1	1.1	3.9	270	9.16	31.3	3.43	2,376
Cottonseed oil (refined)	....	486	650	at 212°F	at 302°F	0.9	....	....	7.5	....	....	....
Cresol m or p	108	202	1,038	1.1	....	1.0	....	395	8.33	29.9	3.58	2,679
Cyclohexane	84	-4	500	at 302°F 1.3	8	0.8	2.9	179	6.66	30.6	4.59	2,323
Cyclohexanone	112	111	788	1.1	....	0.9	3.4	313	7.50	29.3	3.89	2,616
Cymene-para	134	117	817	at 212°F 0.70	....	0.9	4.6	349	7.50	21.9	2.91	3,092
Denatured alcohol	....	60	750	at 212°F	....	0.8	1.6	175	6.66	55.5	8.34	....
Dibutylphthalate o	278	315	757	....	....	1.0+	....	690	8.33	....	....	....
Dichlorobenzene ortho	147	151	1,198	2.2	9.2	1.3	5.1	356	10.83	28.3	2.61	1,258
Diethyl ketone	86	....	....	....	....	0.816[b]	....	216.9[b]	6.79[b]	....	....	....
Dimethyl formamide	73	136	833	2.2	....	0.9	2.5	307	7.50	39.9	5.32	1,774
Dioxane--1,4 (diethylene dioxide)	88	54	356	at 212°F 2.0	22	1.0+	3.0	214	8.33	36.6	4.39	1,793
Ethyl acetate	88	24	800	2.5	9	0.9	3.0	171	7.50	32.9	4.38	1,283
Ethyl alcohol	46	55	793	4.3	19	0.8	1.6	173	6.66	55.5	8.34	1,235
Ethyl ether	74	-49	356	1.9	48	0.7	2.6	95	5.83	29.9	5.12	1,543
Ethyl lactate	118	115	752	1.5	....	1.0+	4.1	309	8.33	27.0	3.28	1,773
Ethyl methyl ether	60	-35	374	at 212°F 2.0	10.1	0.7	2.1	50	5.83	37.0	6.35	1,813
Ethyl propionate	102	54	890	1.9	11	0.9	3.5	210	7.50	28.5	3.8	1,472
Ethylene dichloride	99	56	775	6.2	16	1.3	3.4	183	10.83	42.5	3.92	680
Gasoline	....	-45	495	1.4	7.6	0.8	3.4	100 to 400	6.66	29.6	4.44	2,080
Hexane n	86	-7	453	1.2	7.5	0.7	3.0	156	5.83	25.9	4.44	2,132
Kerosene	....	100	444	0.7	5	< 1.0	....	304 to 574	....	....	....	....
Linseed oil--raw	....	432	650	....	....	0.9	....	600	....	....	....	....
Methyl acetate	74	14	935	3.1	16	0.9	2.6	140	7.50	38.4	5.12	1,188
Methyl alcohol	32	52	867	7.3	36	0.8	1.1	147	6.66	80.7	12.12	1,024
Methyl carbitol	120	200	....	....	....	1.035	4.14	379	8.62	27.9	3.23	....
Methyl cellosolve	76	105	551	....	....	0.966	2.62	255	8.05	40.9	5.08	....
Methyl cellosolve acetate	118	132	....	....	....	1.005	4.07	289	8.38	27.4	3.27	....
Methyl ether	46	Gas	662	3.4	18	....	1.6	-11	....	....	....	....
Methyl ethyl ketone	72	21	960	1.8	10	0.8	2.5	176	6.66	3.33	5.0	1,762
Methyl lactate	104	121	725	2.2	....	1.1	3.6	293	9.16	33.9	3.70	1,507
Mineral spirits No. 10	....	104	473	at 212°F 0.8	....	0.8	3.9	380	6.66	22.6	3.43	2,802
Naphtha (V.M. and P. Regular)	....	20	450	at 212°F 0.92	6.0	0.75	3.73	212 to 320	6.24	22.3	3.58	....
Naphthalene	128	174	979	0.9	5.9	1.1	4.4	424	9.16	27.7	3.02	3,052
Nitrobenzol	123	190	900	1.8	....	1.2	4.3	412	10.0	31.0	3.10	1,689
Nitroethane	75	82	778	at 200°F 4.0	....	1.1	2.6	237	9.16	....	....	....
Nitromethane[e]	61	95 (o.c.)	785	7.3	....	1.1	2.1	214	9.16	58.1	6.34	738
Nitropropane--1	89	120 (o.c.)	789	2.6	....	1.0	3.1	268	8.33	35.8	4.29	1,341
Nitropropane--2	89	103 (o.c.)	802	2.6	....	1.0	3.1	248	8.33	35.8	4.29	1,341
Paraffin oil	....	444	....	....	....	....	....	....	....	....	....	....
Petroleum ether (see benzine)	....	< 0	550	1.1	5.9	0.6	2.5	95 to 140	5.00	26.6	5.37	2,392
Propyl acetate--iso	102	40	860	1.8	8	0.9	3.5	194	7.5	28.5	3.80	1,555
Propyl alcohol n	60	59	700	2.1	13.5	0.8	2.1	207	6.66	42.3	6.35	1,972
Propyl alcohol--iso	60	53	750	2.0	12	0.8	2.1	181	6.66	42.3	6.35	2,073
Propyl ether--iso	102	-18	830	1.4	21	0.7	3.5	146	5.83	22.2	3.81	1,563
Pyridine	79	68	900	1.8	12.4	1.0	2.7	239	8.33	41.1	4.93	2,239
Rosin oil	....	266	648	....	....	1.0	....	> 600	8.33	....	....	....
Soybean oil	....	540	833	....	....	0.9	....	....	7.50	....	....	....
Tetrachloroethane (sym)	168	....	....	....	....	1.6[b]	....	295.3[b]	13.3[b]	....	....	....
Toluol	92	40	997	1.4	6.7	0.9	3.1	231	7.5	32.2	4.29	2,268
Turpentine	....	95	488	0.8	....	< 1	....	300	....	....	....	....
Vinyl acetate	86	18	800	2.6	13.4	0.9	3.0	161	7.5	33.3	4.44	1,248
Xylene (xylol)	106	63	867	1.0	6.0	0.9	3.7	292	7.5	27.0	3.6	2,673

[a] The data in this table have been obtained, with few exceptions as noted, from NFPA Pamphlet No. 325 (1960 Edition): "Fire Hazard Properties of Flammable Liquids, Gases, and Volatile Solids." Available figures from numerous sources will be found to vary over a wide range in many instances, depending on the purity or grade of samples and on the test conditions prescribed by different observers. The figures presented are for information and general guidance only and are not to be regarded as official standards.

The importance of obtaining precise data on the rate of evaporation by actual tests on particular paint formulations in use needs to be emphasized. Some of these multicomponent preparations may contain several solvents with widely different values of "lower explosive limit," "specific gravity," and "vapor density." Until such determinations are made, the operation should be on the side of safety. Therefore, the individual solvent, whose data result in the largest required volume of air per gallon, should be used as the basis for safe ventilation. Corrections and factors of safety for final ventilation values are to be applied as indicated in the other footnotes.

[b] Handbook of Chemistry, 9th ed., 1956, Lange.

[c] For final required safety ventilation values in each particular oven operation, these figures are multiplied by the following factors as they apply: 1. Temperature--Volume Conversion, 2. Standard factor of safety of 4 for continuous process ovens, 1. LEL Correction factor for batch ovens between 250° and 500°F multiply by 1.4, 4. The maximum number of gallons of solvent evaporated per unit of time on the basis of maximum possible loadings.

[d] Column J gives the cubic feet of air rendered barely explosive by 1 gallon of solvent. For most practical calculations, however, this value is close enough to the actual volume of the vapor-air mixture.

[e] Classified as a potentially explosive chemical (see NBFU Research Report No. 12, Nitroparaffins and their Hazards).

and $\frac{2,825(460 + 375)}{(460 + 70)}$ = 4,450 ft^3/gal at 375°F

The safety factor is $\frac{61,017}{4,450}$ = 13.7

Thus, the volume exhausted is satisfactory, being well above the required safety factor of 4.

6. Quantity of particulate matter per cubic foot of contaminated air exhausted from the oven:

Assume that 20 percent of the solvent evaporated in the paint-baking oven is incinerated and 80 percent is exhausted. Hence, 206 pounds of solvent used per day x 40 percent charged to the oven x 80 percent exhausted equals 65.9 pounds of solvent exhausted from the oven per day.

The amount of particulate matter that may be formed from solvents evaporated in a paint-baking oven can be predicted from Figure 524. The graph indicates that 385 grains of particulate matter is formed per pound of solvent evaporated at 375°F.

$\frac{(65.9)(385)}{720,000}$ = 0.0353 grain/ft^3 at 375°F

and $\frac{(0.0353)(460 + 375)}{(460 + 60)}$ = 0.057 grain/scf

7. Check the oven heat load against the rated capacity of the burner supplied with the oven:

(a) Heat loss to the surrounding air from the oven surfaces:

$$Q_1 = UA\Delta T$$

where

U = overall heat transfer coefficient, Btu/hr per ft^2 per °F

A = outside oven area, ft^2

ΔT = temperature difference between inside of oven and ambient air.

Total outside oven area:

9 ft x 27 ft x 2 = 486 ft^2
4 ft x 27 ft = 108

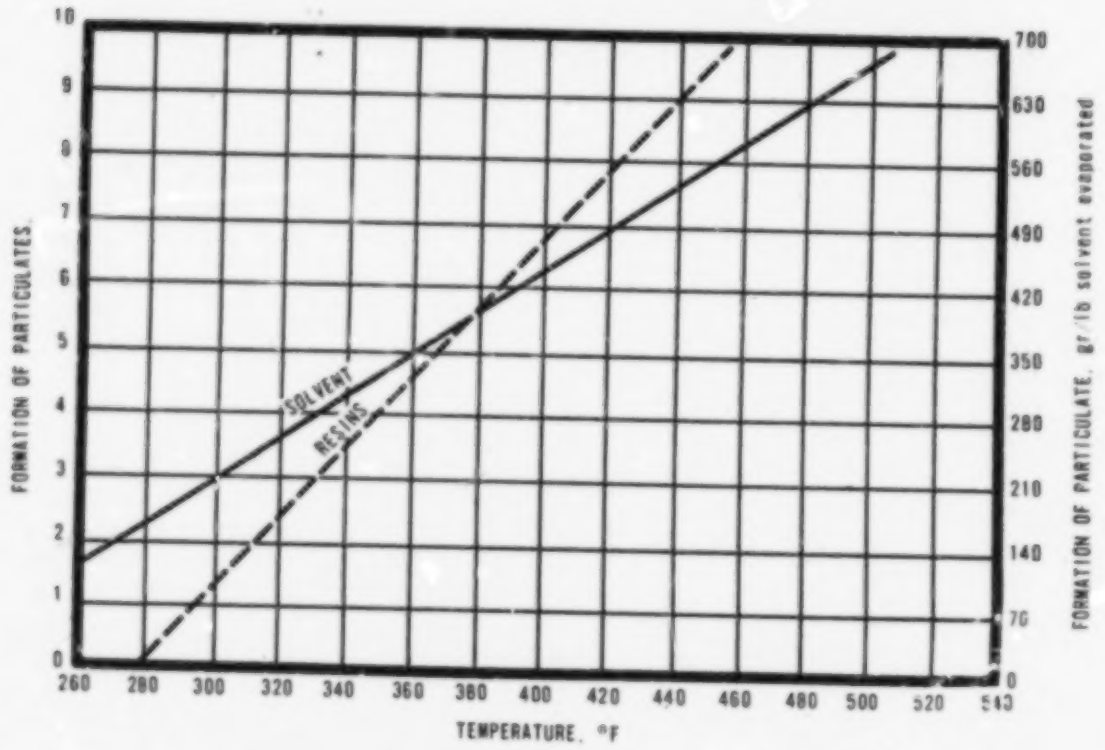


Figure 524. Formation, %, of particulate matter from solvents or resins evaporated in paint-baking oven.

9 ft x 17 ft x 2 = 306
4 ft x 17 ft = 68
9 ft x 14 ft x 2 = 252
5 ft - 4 in. x 14 ft = 75
1,295 ft^2

U = 0.66 Btu/hr per ft^2 per °F (given)
Q_1 = (0.66)(1,295)(375-60)
= 269,230 Btu/hr

(b) Heat required to raise the material being processed to the baking temperature:

$$Q_2 = W_1 C_{p1} \Delta t_1 + W_2 C_{p2} \Delta t_2 + W_3 h_v$$

where

W_1 = wt of steel parts = 20,000 lb/8 hr = 2,500 lb/hr

C_{p1} = specific heat of steel = 0.12 Btu/lb per °F

Δt = $(T_1 - T_2)$ = 375 - 60°F = 315°F

and W_2 = the wt of thinned, partially dried enamel adhered to the metal parts entering the oven per hour. This is composed of the 40 percent of the solvent chargeable to the oven (see step 2) plus the nonvolatile portion of the enamel.

$\frac{(11.8 \text{ gal/day})(7 \text{ lb/gal})}{8 \text{ hr/day}}$ = 10.3 lb solvent per hr

$\frac{(32 \text{ gal/day})(9.2 \text{ lb/gal})(51\%)}{8 \text{ hr/day}}$ = 18.8 lb nonvolatile per hr

10.3 lb/hr + 18 lb/hr = 29.1 lb/hr enters the oven

C_{p2} = the specific heat of thinned, partially dried enamel, which is assumed to be 0.5 Btu/lb per °F

Δt_2 = 315°F

and W_3 = wt of solvent per hr that is evaporated in the oven is 10.3 lb/hr

h_v = the heat of vaporization of the solvent, which is assumed to be 150 Btu/lb

Q_2 = (2,500)(0.12)(315) + (29.1)(0.5)(315) + (10.3)(150) = 100,626 Btu/hr

(c) Heat required for oven makeup air:

$$Q_3 = W_4 C_{p4} \Delta t$$

where

W_4 = weight of fresh air

$$= (0.0755)\frac{\text{lb}}{\text{ft}^3}(1,500)\frac{\text{ft}^3}{\text{min}}(60)\frac{\text{min}}{\text{hr}}\frac{460 + 60}{460 + 375}$$

= 4,233 lb/hr

C_{p4} = average specific heat of air = 0.24 Btu/lb - °F

Δt = 315°F

Q_3 = (4,233)(0.24)(315) = 320,015 Btu/hr

(d) Total oven heat load:

$Q_t = Q_1 + Q_2 + Q_3$ = 269,230 + 100,626 + 320,015 = 689,870 Btu/hr

The burner supplied is rated at 1,200,000 Btu/hr and is ample for this application.

8. Mass flow rate of the contaminated gases from the oven to the direct-flame afterburner:

$$\frac{(1,500)(60)(460 + 60)}{(460 + 375)} = 56,050 \text{ ft}^3/\text{hr}$$

9. Heat required to increase the temperature of the gases from 375° to 1,400°F:

An afterburner operating temperature of 1,400°F is usually sufficient to incinerate the air contaminants emitted by most paint-baking ovens.

Use air enthalpies as shown in Table D4 in Appendix D.

Enthalpy of air at 1,400°F = 26.13 Btu/ft^3
Enthalpy of air at 375°F = 5.83 Btu/ft^3
Δh = 20.30 Btu/ft^3

(56,050)(20.3) = 1,137,815 Btu/hr

10. Heat losses from afterburner due to radiation, convection, and conduction:

    Losses equal to 15 percent of the total heat input are assumed. This is a conservative estimate for afterburners constructed of firebrick or castable refractory and operated at 1,400°F.

    $(1,137,815)(0.15) = 170,670$ Btu/hr

11. Total heat required by the afterburner:

    $1,137,815 + 170,670 = 1,308,485$ Btu/hr

12. Required natural gas volume capacity of the burner:

    Because of the large volume of air used to dilute the organic solvent vapor in the oven, the contaminated gases contain sufficient oxygen to furnish all the combustion air needed for the proper combustion of the natural gas supplied to the burner. The natural gas is, therefore, supplied with theoretical air from the contaminated gas stream from the oven. This is introduced through a premix combustion air blower.

    Not only does this provide excellent mixing, but it has an added advantage in that the effluent that goes through the burner itself also goes through the hottest area in the afterburner, even though only momentarily.

    The gross heating value of the natural gas is assumed to be 1,100 Btu/ft^3. The net heat available at 1,400°F from the burning of 1 cubic foot of natural gas under these conditions is 939 Btu (see Table C1 in Appendix C).

    $$\frac{1,308,485}{939} = 1,395 \text{ ft}^3/\text{hr}$$

13. Volume of natural gas at 1,400°F:

    With theoretical air, 1 ft^3 of natural gas yields 11.45 ft^3 of products of combustion (see Table D7 in Appendix D).

    $$\frac{(1,395)(11.45)(1,400 + 460)}{(3,600)(60 + 460)} = 15.9 \text{ ft}^3/\text{sec}$$

14. Volume of contaminated gas at 1,400°F:

    Mass flow rate = 56,050 ft^3/hr
    Effluent used for combustion air:

    Theoretical air required = $10.36 \frac{\text{ft}^3}{\text{ft}^3 \text{ of gas}}$ (see Table D7 in Appendix D).

    Total effluent used = $(1,395) \frac{\text{ft}^3}{\text{hr}} (10.36) =$ 14,452 ft^3/hr

    Volume of contaminated gas = 56,050 − 14,452 = 41,598 ft^3/hr at 60°F

    $$= \frac{41,598}{3,600} \frac{(1,400 + 460)}{(60 + 460)} = 41.5 \text{ ft}^3/\text{sec at } 1,400°\text{F}$$

15. Total volume of gases in the afterburner:

    $15.9 + 41.5 = 57.4$ ft^3/sec

16. Diameter of afterburner orifice:

    The effluent from paint-baking ovens demands vigorous treatment if it is to be rendered innocuous. Orifice velocities of 40 to 60 ft/sec are, therefore, recommended in order to provide adequate mixing of contaminated gases with the burner's combustion products. Use a design velocity of 50 ft/sec:

    Cross-sectional area = $\frac{57.4}{50} = 1.15$ ft^2

    Diameter = $2\sqrt{\frac{(1.15)(144)}{3.1416}} = 14.5$ in.

17. Diameter of the afterburner's combustion chamber:

    Combustion chamber velocities of 20 to 30 ft/sec have been found sufficient to provide adequate turbulence for completing combustion and to allow the construction of an afterburner of reasonable length in order to obtain the required residence time. Use a design velocity of 25 ft/sec:

    Cross-sectional area = $\frac{57.4}{25} = 2.3$ ft^2

    Diameter = $2\sqrt{\frac{(2.3)(144)}{3.1416}} = 20.5$ in.

18. Length of afterburner's combustion chamber:

    Use a design retention time of 0.5 second:

    Length = $(25)(0.5) = 12.5$ ft

Problem note: A comparison of the total oven heat load (689,870 Btu/hr) with the total heat required to operate the afterburner (1,308,485 Btu/hr) indicates the possibility of salvaging heat from the afterburner to provide part or all of the oven's heat demand. This may be accomplished in several ways or in a combination of the following ways:

(a) The fresh makeup air for the oven can be directed through a heat exchanger placed downstream from the afterburner's exhaust.

(b) The oven's effluent can be preheated before entering the afterburner by providing a heat exchanger downstream from the afterburner.

(c) A portion of the hot discharge stream from the afterburner can be diverted, mixed with the fresh makeup air, and recirculated through the oven to provide all the heat required by the oven. This is a desirable method of conserving heat energy since it has a high efficiency and a low equipment cost.

(d) The heat from the afterburner can also be made available for a variety of plant processes other than the paint-baking oven.

SOAPS AND SYNTHETIC DETERGENTS

SOAPS

Soaps consist principally of sodium or potassium salts of fatty acids containing 12 to 18 carbon atoms (Kirk and Othmer, 1947). The soaps are made by reacting sodium or potassium hydroxide with fats or oils (saponification). They can also be prepared by neutralizing fatty acids with sodium or potassium hydroxide or sodium carbonate. Generally, sodium soaps are referred to as hard soaps, and potassium soaps, as soft or liquid soaps. Technical developments in the industry now enable sodium soaps to be made with all the properties of a soft-type soap.

Soaps are produced in a number of different, but not sharply defined, grades. The best grades are toilet or castile soaps. These are made in a bar, paste, or liquid form and contain little or no alkali. The next grade is made in bars, flakes, granules, or powders. This type of soap is used for dishwashing and laundering woolens or fine fabrics. This soap is also essentially pure. It is prepared from darker (lower grade) fats than toilet soap are and contains a slight amount of free alkali. The amount of alkali should be limited to prevent skin irritation. Laundry soaps comprise the third grade. They are prepared from the darker fats and contain relatively large amounts of free alkali. These soaps are also available in cake, flake, granule, or powder form. Laundry soaps also contain "builders," which lower costs and aid in the detergent action. Builders include soda ash, sodium silicate, sodium tripolyphosphate, and tetrasodium pyrophosphate. These builders are added for optimum soil removal and act as water softeners as well as cleaning agents.

Raw Materials

Tallow constitutes about half of the fats and oils consumed by the soap industry (Molos, [illegible] Tallow is a mixture of glycerides obtained by steam rendering cattle fat and, to a lesser extent, sheep fat. Greases are second in volume of fatty material used, comprising about 20 percent of the total. Greases are generally obtained from hogs, small domestic animals, and garbage. These greases are obtained by steam rendering or solvent extraction. Usually the greases, tallows, and other fats are blended (Shreve, 1956).

Coconut oil is the third-ranking source of fatty acids. It is usually blended with tallow to increase the solubility of the soap. Other oils used include palm, palm-kernel, Babassu nut, cottonseed, soya bean, and peanut (Shreve, 1956).

Fatty Acid Production

Fats and oils may be hydrolyzed or "split" to obtain fatty acids and glycerol. Separated fatty acids can then be used for soap or other products. Three general methods are available to hydrolyze the fats and oils: Twitchell, batch autoclave, and continuous high-pressure process.

The Twitchell process consists of boiling the fats and oils batchwise in an open tank for 20 to 48 hours with 0.75 to 1.25 percent Twitchell's reagent and 0.5 percent sulfuric acid. Twitchell's reagent consists of alkyl-aryl sulfonic acid or cycloaliphatic sulfonic acids. Enough water is used to yield a 5 to 15 percent glycerin solution. The reaction is usually completed in two countercurrent stages. The aqueous solution containing the glycerine is withdrawn after settling, neutralized with slaked lime, and filtered to remove the calcium sulfate. The glycerine liquor is concentrated by evaporation. The fatty acid fraction is decanted from the upper phases.

The batch autoclave process operates under pressures ranging from 75 to 150 psi and temperatures of 300° to 350°F. An oxide catalyst of zinc, calcium, or manganese is used in the amount of 1 to 2 percent of the batch by weight. Higher pressures (425 to 450 psi) and temperature (450°F) are required if no catalyst is used. Each batch requires from 5 to 10 hours.

The continuous high-pressure process for splitting fats and oils is done in a vertical column. After the fats and oils are vacuum deaerated to prevent darkening, they are charged to the bottom of the column through a sparge ring. Deaerated, demineralized water is charged to the top of the tower. High-pressure live steam is injected into the reaction zone, approximately the midpoint of the tower, where the fats and oils are split into fatty acids and glycerine. A pressure of 600 to 700 psi and a temperature of approximately 485°F are required. The oil droplets, entering the bottom of the tower through the sparge ring, rise up through the water-glycerine solution because of lower density. The water-glycerine is drawn off at the bottom of the tower. As the oil droplets rise, the glycerides split, and the freed fatty acids are separated from the glycerine, which dissolves in the incoming water. The fatty acids pass overhead to a decanter where any entrained water is removed.

The mixed fatty acids obtained by these processes can be used directly in soap manufacture or they can be separated into more refined fractions (palmitic acid, stearic acid, oleic acid, and others). Steam distillation, pressing, or fractional-crystallization methods are practical.

Soap Manufacture

The kettle or full-boiled batch process is the most widely used and oldest method of soap manufacture. First, the molten fats are boiled in a caustic solution by using live steam. After saponification of the fats and oils to soap and glycerine is essentially completed, salt is added to separate the soap from the aqueous phase. The soap is settled by gravity, and the glycerine phase is drawn off. After the batch is diluted with water, the mixture is reboiled. The aqueous layer is again drawn off. Strong caustic can then be added if required. The mixture is again boiled and settled, and the aqueous layer is removed. This aqueous layer contains excess caustic and can be used in later batches. The soap mixture is again diluted with water, reboiled, and allowed to settle. Three layers settle out. The upper layer is the crude product sometimes called neat soap. The middle layer, called nigre, is dark colored and strongly alkaline. The bottom layer is primarily caustic though it may contain some soap. The nigre can be used in cheaper, darker grades of soap or used in the next batch.

The Sharples process, an adaptation of the full-boiled process, makes soap continuously. Centrifuges are used to separate the soap from the aqueous phases. The total process time is reduced from several days to a few hours. Four stages corresponding to the four stages of the kettle process are used. The flow of the caustic is countercurrent to the flow of fats and oils.

The semi-boiled process involves the boiling of fats and oils with the theoretically required caustic. No washing of glycerine is done. The cold-make process is similar to the semi-boiled operation, except that the components are mixed in a crutcher (a type of mixer) and run into frames, where saponification is completed over several days at room temperatures up to 110°F.

Any free fatty acids must then be neutralized by caustic soda or soda ash. The amount of caustic added must be carefully controlled to limit free-caustic concentration in the final product to 0.02 to 0.10 percent.

Soap Finishing

Soap is finished in many forms--bars, flakes, granules, liquids, or powder.

Neat soap contains approximately 30 percent moisture and must be dried in hot-air driers, spray driers, or steam-heated tubes. The hot-air process is used to make bar soap, soap chips, and soap flakes. Liquid soap is charged through a chilled roller. The thin film formed is stripped off in ribbons by a serrated scraper knife. The ribbons fall to a wire screen conveyor that carries them through the drier in several passes. The ribbons are then air cooled and carried to storage by screw conveyors, which break the soap ribbons into chips.

When bar or flake form is desired, the soap chips are charged to mixers. Here perfumes, dyes, pigments, and preservatives are added. Next, the material is rolled in granite- or steel-roll mills. The milled chips are made into bars by extrusion through a die. As it emerges in a continuous bar, the soap is cut or stamped into cakes. If soap flakes are desired, the chips are taken from the finishing roll as a very thin film and cut into flakes.

Spray drying is a widely used method of finishing soap. After alkalinity builders are mixed with the neat soap, special high-pressure pumps force

it through high spray towers. Hot air, 500°F, is blown countercurrently or concurrently to the falling droplets. The sprayed soap dries into a powder.

SYNTHETIC DETERGENTS

The surface-active agents most commonly known as detergents can be grouped into five main chemical classes, as shown in Table 208. The classification is based upon the ionic properties. Anionic detergents ionize in water to give a negatively charged organic ion and can be subclassified as sulfated fatty alcohols, alkyl-aryl sulfonates, and miscellaneous sulfates and sulfonates Another class is the cationic synthetics, which yield positively charged ions in the presence of water. Detergents that do not ionize comprise the final group.

Detergents contain from 20 to 40 percent active agent. The remainder includes builders, fillers, dye, and other compounds. The most common builders are again sodium tripolyphosphate and tetrasodium pyrophosphate. Sodium carboxymethyl cellulose can be added to obtain better dirt suspension properties. Sodium silicate is added to counter corrosion in aluminum washing machines.

The largest selling type of detergent base, alkyl-aryl sulfonate, is prepared from an aromatic hydrocarbon and polymerized straight-chain hydrocarbon. Necessary water solubility is obtained by sulfonating the water-insoluble hydrocarbon product, usually an alkylated benzene. A flow diagram of this process is shown in Figure 525. It involves reacting dodecene and benzene in the presence of an aluminum chloride catalyst. The desired boiling range of dodecylbenzene is obtained by fractionation. This product is sulfonated and neutralized with caustic. Builders are added to the slurry, and the product is dried. A flake finish is obtained by drum drying, and a bead-shaped product is obtained by spray drying.

Biodegradable linear alkylbenzene sulfonate can be prepared from kerosine and benzene. The kerosine is chlorinated in the presence of an iodine catalyst. The monochlorinated kerosine is then reacted with benzene by using aluminum chloride catalyst. Fractionation, sulfonation, and neutralization cycles then complete the process. These softer linear detergents have less foaming tendencies than do the hard synthetic detergents.

Detergents can also be prepared by a hydrogenation process from base stocks derived from coconut oil and alcohol (Niven, 1955). The reaction rate is controlled to maintain the unreacted ester in slight excess. The next step is hydrolysis of the reacted product. The top layer, containing product and reducing alcohol, is separated by distillation. The product is then sulfonated with concentrated sulfuric acid or liquid SO_3. The sulfate produced is then converted to a salt with alkali. Excess sodium sulfate can be removed or left as a filler. The product is then dried.

THE AIR POLLUTION PROBLEM

Soaps

The principal air pollution problem in the preparation of soap is odors. The extent of the odor problem depends upon the type of charge stock. Low-grade stocks obtained from rendered greases and fats tend to be more odoriferous. In an at-

Table 208. SYNTHETIC DETERGENTS

Classification	Ionization with water	Trade names	Main uses
Sulfated fatty alcohols	Negative	Orvus, Dreft, Duponal, etc	Strong soap competitors
Alkyl-aryl sulfonates	Negative	Oronite, Ultrawet, Santomerse, Tide, Fab, Surf, Cheer, etc	Low-price cleaners for home and industry
Miscellaneous sulfates and sulfonates	Negative	Merpols, MP-189, Arctic Snytex, Vel, Igepon A, Igepon T, etc	Cleaners with hard water, excellent soil removers
ationic agents	Positive	---	Germicidals
Nonionic agents	Do not ionize	Spans, Tweens, Glim, Triton, etc	Soil removers and grease emulsifiers (low foam)

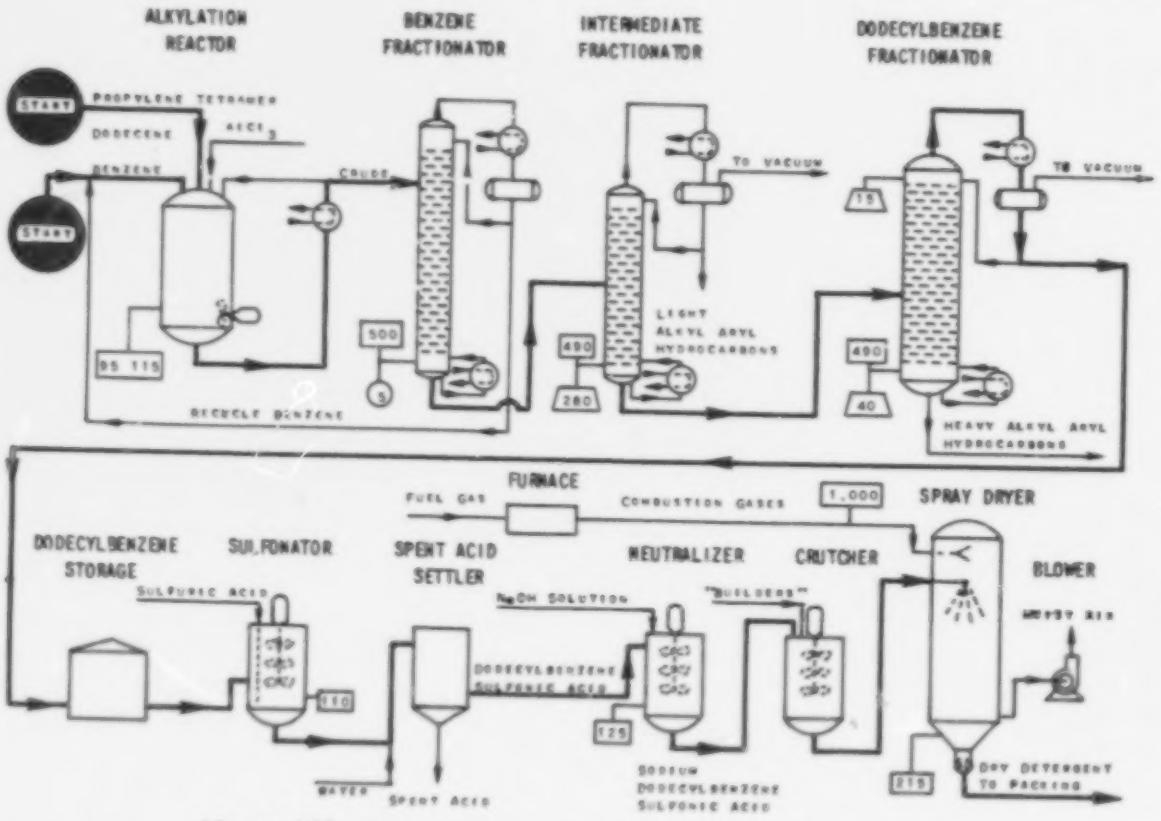


Figure 525. Flow sheet for alkyl-aryl sulfonate (Anon., 1961. Copyrighted by Gulf Publishing Co., Houston, Texas).

tempt to obtain a better smelling product, soap manufacturers sometimes employ a deodorizer. The undesirable components are removed by means of live steam or a vacuum.

Blending, mixing, and packaging the finished soap can cause local dust problems.

Detergents

The air pollution problems encountered in preparing the base stocks are similar to those associated with a petroleum refinery. Relief valves, storage vessels, and pump seals can allow volatile hydrocarbons to escape to the atmosphere. Some of the fractionating equipment is operated at atmospheric or under vacuum conditions. The vents from accumulators or vacuum-producing equipment are a source of pollution. When kerosine is chlorinated, chlorine and hydrogen chloride gas are vented from the chlorinator.

Equipment to handle the spent aluminum chloride complexes must be provided. The complex is first hydrolyzed and then the acid water may have to be neutralized. The equipment used in this operation can be a source of air pollution. The hydrolysis phase requires agitation and is exothermic. Hydrogen chloride and hydrocarbon vapors can be released during this period. Air is normally agitated when neutralization is necessary, and the vented air can be a source of odors.

AIR POLLUTION CONTROL EQUIPMENT

Soaps

Odors can be most successfully controlled by incineration. Condensation can be employed as an auxiliary to incineration. The effluent from soap kettles, Twitchell tanks, and high-pressure splitters contains large amounts of steam. By condensing part or all of the steam, the volume of effluent to be incinerated is greatly reduced. Part of the odorous material is condensed or knocked down by the condensing steam. Contact-type condensers should be avoided unless the contaminated water can be directly sewered. In any event the contaminated water should not be cooled in a cooling tower or spray pond.

The most economical method of incineration consists of venting the noncondensable effluent into the firebox of a continuously operating boiler. Complete destruction of the odors is achieved if the effluent is injected as part

of the combustion air. A temperature of 1,200°F should be maintained at the exit of the combustion chamber.

Absoprtion of odors in scrubbing liquids has been tried with varying success. One fatty acid plant tried an alkaline scrubber on the assumption that the odorous materials were acid; benefits were negligible. In a soap plant using the Sharples continuous soap-making process, the odorous substances were identified as low-boiling amines (Molos, 1961). A scrubber using a sulfuric acid solution at a pH of 2 was successful in removing odors from the centrifuge room and from the spray drier effluent. Apparently, the success of odor removal by scrubbing depends upon identifying the odorous substances and finding a scrubbing liquid that reacts rapidly and completely with these substances.

In the finishing operations, dust is the principal air pollution problem. Of these operations, spray drying has the greatest air pollution potential. Granulating, screening, conveying, and mixing dry soap and other dry ingredients create sufficient dust to require an extensive dust collection and control system.

Spray driers are usually controllable by scrubbers. A high-efficiency scrubber, such as a venturi scrubber, is required to ensure the collection of the very fine particles. Centrifugal collectors are usually used ahead of the scrubber in order to collect as much material as possible in the dry form.

Reject soap bars and chips are sometimes ground in a screen-type hammer mill. The ground soap is used in industrial and laundry blends. The mill discharge is screened, and the oversize particles are recycled to the mill. Since soap dust is irritating to the nasal passages, this operation requires very good dust control. The mill and the screen must be kept under suction, and any open transfer points must be hooded. A baghouse is the usual collector for this service. The collected dust can be combined with the product.

Detergents

Relief valves can be vented to a smokeless flare. Atmospheric vents on condensers and accumulators can be controlled by connecting the vent to a vapor recovery system or by using a heliflow water condenser. Vacuum jets are vented to the firebox of heaters. Barometric legs should also be sealed off and the vapors incinerated. Centrifugal pumps should be equipped with mechanical seals and properly maintained.

The hydrolyzing and neutralizing equipment should be vented to a properly designed water scrubber.

GLASS MANUFACTURE

Glass has been made for over 3,500 years, but only in the last 75 years have engineering and science been able to exploit its basic properties of hardness, smoothness, and transparency so that it can now be made into thousands of diverse products.

The economics and techniques connected with mass production of glass articles have led to the construction of glass-manufacturing plants near or within highly populated areas. Unfortunately, airborne contaminants generated by these glass plants can contribute substantially to the air pollution problem of the surrounding community. Control of dust and fumes has, therefore, been, and must continue to be, inherent to the progress of this expanding industry.

Air pollution control is necessary, not only to eliminate nuisances, but also to bring substantial savings by extending the service life of the equipment and by reducing operating expenses and down time for repair. Reduction in plant source emissions can be accomplished by several methods, including control of raw materials, batch formulation, efficient combustion of fuel, proper design of glass-melting furnaces, and the installation of control equipment.

TYPES OF GLASS

Nearly all glass produced commercially is one of five basic and broad types: Soda-lime, lead, fused silica, borosilicate, and 96 percent silica. Of these, modern soda-lime glass is well suited for melting and shaping into window glass, plate glass, containers, inexpensive tableware, electric light bulbs, and many other inexpensive, mass-produced articles. It presently constitutes 90 percent of the total production of commercial glass (Kirk and Othmer, 1947).

Typical compositions of soda-lime glass and the four other major types of commercial glass are shown on Table 209. Major ingredients of soda-lime glass are sand, limestone, soda ash, and cullet. Minor ingredients include salt cake, aluminum oxide, barium oxide, and boron oxide. Minor ingredients may be included as impurities in one or more of the major raw ingredients.

Table 209. COMPOSITIONS OF COMMERCIAL GLASSES (Kirk and Othmer, 1947)

Component	Composition, %[a]				
	Soda-lime	Lead	Borosilicate	96% silica	Silica glass
SiO_2	70 to 75 (72)	53 to 68 (68)	73 to 82 (80)	96	99.8
Na_2O	12 to 18 (15)	5 to 10 (10)	3 to 10 (4)	-	-
K_2O	0 to 1	1 to 10 (6)	0.4 to 1	-	-
C_aO	5 to 14 (9)	0 to 6 (1)	0 to 1	-	-
PbO	-	15 to 40 (15)	0 to 10	-	-
B_2O_3	-	-	5 to 20 (14)	3	-
Al_2O_3	0.5 to 2.5 (1)	0 to 2	2 to 3 (2)	-	-
M_gO	0 to 4 (3)	-	-	-	-

[a]The figures in parentheses give the approximate composition of a typical member.

Soda-lime glasses are colored by adding a small percentage of oxides of nickel, iron, manganese, copper, and cobalt, and elemental carbon as solutions or colloidal particles (Tooley, 1953).

Although glass production results in tens of thousands of different articles, it can be divided into the following general types (Kirk and Othmer, 1947):

	%
Flat glass	25
Containers	50
Tableware	8
Miscellaneous instruments, scientific equipment, and others	17

GLASS-MANUFACTURING PROCESS

Soda-lime glass is produced on a massive scale in large, direct-fired, continuous melting furnaces. Other types of glass are melted in small batch furnaces having capacities ranging from only a few pounds to several tons per day. Air pollution from the batch furnaces is minor, but the production of soda-lime glass creates major problems of air pollution control.

A complete process flow diagram for the continuous production of soda-lime glass is shown on Figure 526. Silica sand, dry powders, granular oxides, carbonates, cullet (broken glass), and other raw materials are transferred from railroad hopper cars and trucks to storage bins. These materials are withdrawn from the storage bins, batch weighed, and blended in a mixer. The mixed batch is then conveyed to the feeders attached to the side of the furnace. Although dust emissions are created during these operations, control can be accomplished by totally enclosing the equipment, and installing filter vents, exhaust systems, and baghouses.

Screw- or reciprocating-type feeders continuously supply batch-blended materials to the direct-fired, regenerative furnace. These dry materials float upon the molten glass within the furnace until they melt. Carbonates decompose releasing carbon dioxide in the form of bubbles. Volatilized particulates, composed mostly of alkali oxides and sulfates, are captured by the flame and hot gases passing across the molten surface. The particulates are either deposited in the checkers and refractory-lined passages or expelled to the atmosphere.

The mixture of materials is held around 2,700°F in a molten state until it acquires the homogeneous character of glass. Then it is gradually cooled to about 2,200°F to make it viscous enough to form. In a matter of seconds, while at a yellow-orange hot temperature, the glass is drawn from the furnace and worked on forming machines by a variety of methods including pressing, blowing in molds, drawing, rolling, and casting.

One source of air pollution results from the use of hydrocarbon greases and oils to lubricate the hot delivery systems and molds of glass-forming machines. The smoking from these greases and oils creates a significant source of air pollution separate from furnace emissions.

Immediately after being shaped in the machines, the glass articles are conveyed to continuous annealing ovens, where they are heat treated to remove strains that have developed during the molding or shaping operations and then subjected to slow, controlled cooling. Gas-fired or electrically heated annealing ovens are not emitters of air contaminants in any

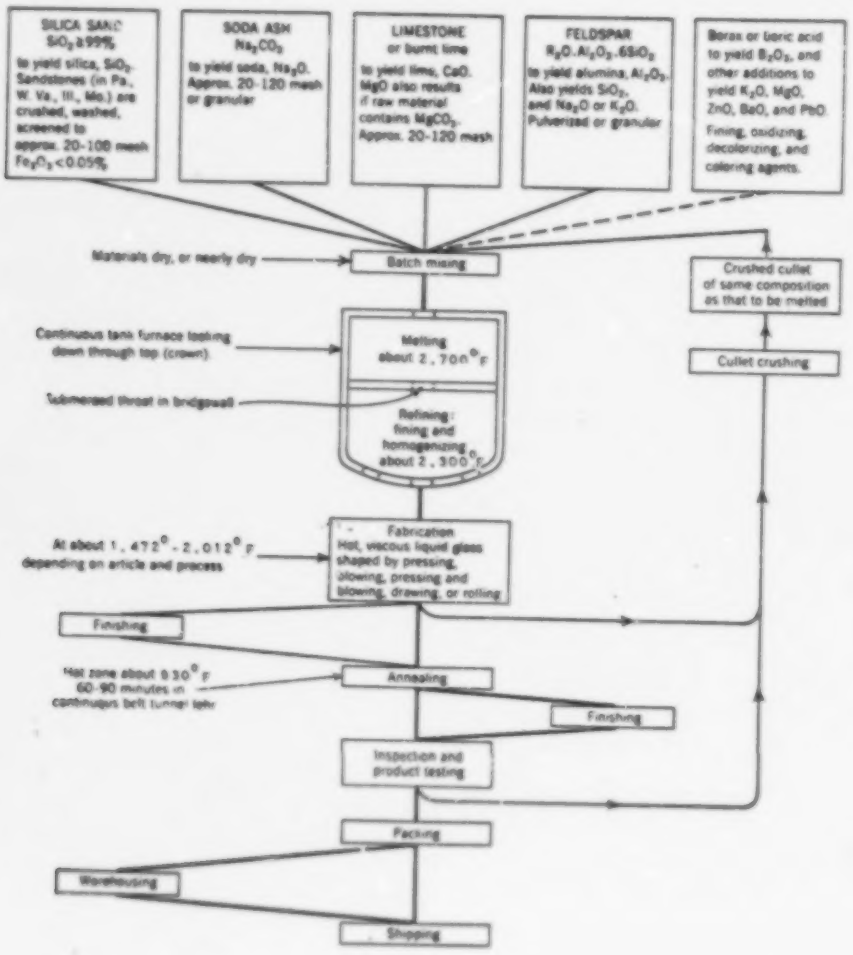

SILICA SAND
SiO_2 ≥ 99%
to yield silica, SiO_2.
Sandstones (in Pa., W. Va., Ill., Mo.) are crushed, washed, screened to approx. 20-100 mesh
Fe_2O_3 < 0.05%
SODA ASH
Na_2CO_3
to yield soda, Na_2O.
Approx. 20-120 mesh or granular
LIMESTONE
or burnt lime
to yield lime, CaO.
MgO also results if raw material contains $MgCO_3$.
Approx. 20-120 mesh
FELDSPAR
$R_2O.Al_2O_3.6SiO_2$
to yield alumina, Al_2O_3.
Also yields SiO_2, and Na_2O or K_2O.
Pulverized or granular
Borax or boric acid to yield B_2O_3, and other additions to yield K_2O, MgO, ZnO, BaO, and PbO.
Fining, oxidizing, decolorizing, and coloring agents.
Materials dry, or nearly dry
Batch mixing
Crushed cullet of same composition as that to be melted
Cullet crushing
Continuous tank furnace loading down through top (crown).
Submerged throat in bridgewall
Melting about 2,700°F
Refining: fining and homogenizing about 2,300°F
At about 1,472°-2,012°F depending on article and process
Fabrication
Hot, viscous liquid glass shaped by pressing, blowing, pressing and blowing, drawing, or rolling
Finishing
Hot zone about 930°F
60-90 minutes in continuous belt tunnel lehr
Annealing
Finishing
Inspection and product testing
Packing
Warehousing
Shipping

Figure 526. Flow diagram for soda-lime glass manufacture (Kirk and Othmer, 1947).

significant quantity. After leaving the annealing ovens, the glass articles are inspected and packed or subjected to further finishing operations.

Glass-forming machines for mass production of other articles such as rod, tube, and sheet usually do not emit contaminants in significant amounts.

HANDLING, MIXING, AND STORAGE SYSTEMS FOR RAW MATERIALS

Material-handling systems for batch mixing and conveying materials for making soda-lime glass normally use commercial equipment of standard design. This equipment is usually housed in a structure separate from the glass-melting furnace and is commonly referred to as a "batch plant." A flow diagram of a typical batch plant is shown in Figure 527. In most batch plants, the storage bins are located on top, and the weigh hoppers and mixers are below them to make use of the gravity flow.

Major raw materials and cullet (broken scrap glass) are conveyed from railroad hopper cars or hopper trucks by a combination of screw conveyors, belt conveyors, and bucket elevators, or by pneumatic conveyors (not shown in Figure 527) to the elevated storage bins. Minor ingredients are usually delivered to the plant in paper bags or cardboard drums and transferred by hand to small bins.

Ingredients comprising a batch of glass are dropped by gravity from the storage bins into weigh hoppers and then released to fall into the mixer. Cullet is ground and then mixed with the dry ingredients in the mixer. Ground cullet may also bypass the mixer and be mixed instead with the other blended materials in the bottom of a bucket elevator. A typical batch charge for making soda-lime flint glass in a mixer with a capacity of 55 cubic feet consists of:

	lb
Silica sand	2,300
Cullet	650
Soda ash	690

Limestone	570
Niter	7
Salt cake	12
Arsenic	2
Decolorizer	1
	4,232

Raw materials are blended in the mixer for periods of 3 to 5 minutes and then conveyed to a charge bin located alongside the melting furnace. At the bottom of the charge bin, rotary valves feed the blended materials into reciprocating- or screw-type furnace feeders.

In a slightly different arrangement of equipment to permit closer control of batch composition, blended materials are discharged from the mixer into batch cans that have a capacity of one mixer load each. Loaded cans are then conveyed by monorail to the furnace feeders. Trends in batch plant design are toward single reinforced-concrete structures in which outer walls and partitions constitute the storage bins. Complete automation is provided so that the batch plant is under direct and instant control of the furnace foreman.

THE AIR POLLUTION PROBLEM

The major raw materials for making soda-lime glass--sand, soda-ash, and limestone--usually contain particles averaging about 300 microns in size. A small percentage of these particles, however, is less than 50 microns but present in sufficient quantities to cause dust emissions during conveying, mixing, and storage operations. Moreover, minor raw materials such as salt cake and sulfur can create dust emissions during handling. Dust is the only air contaminant from batch plants, and control of dust emissions poses problems similar to those in industrial plants handling similar dusty powder or granular materials.

HOODING AND VENTILATION REQUIREMENTS

Dust control equipment can be installed on conveying systems that use open conveyor belts. A considerable reduction in the size of the dust control equipment can be realized by totally enclosing all conveying equipment and sealing all covers and access openings with gaskets of polyurethane foam. In fact, by totally enclosing all conveying equipment, exhaust systems

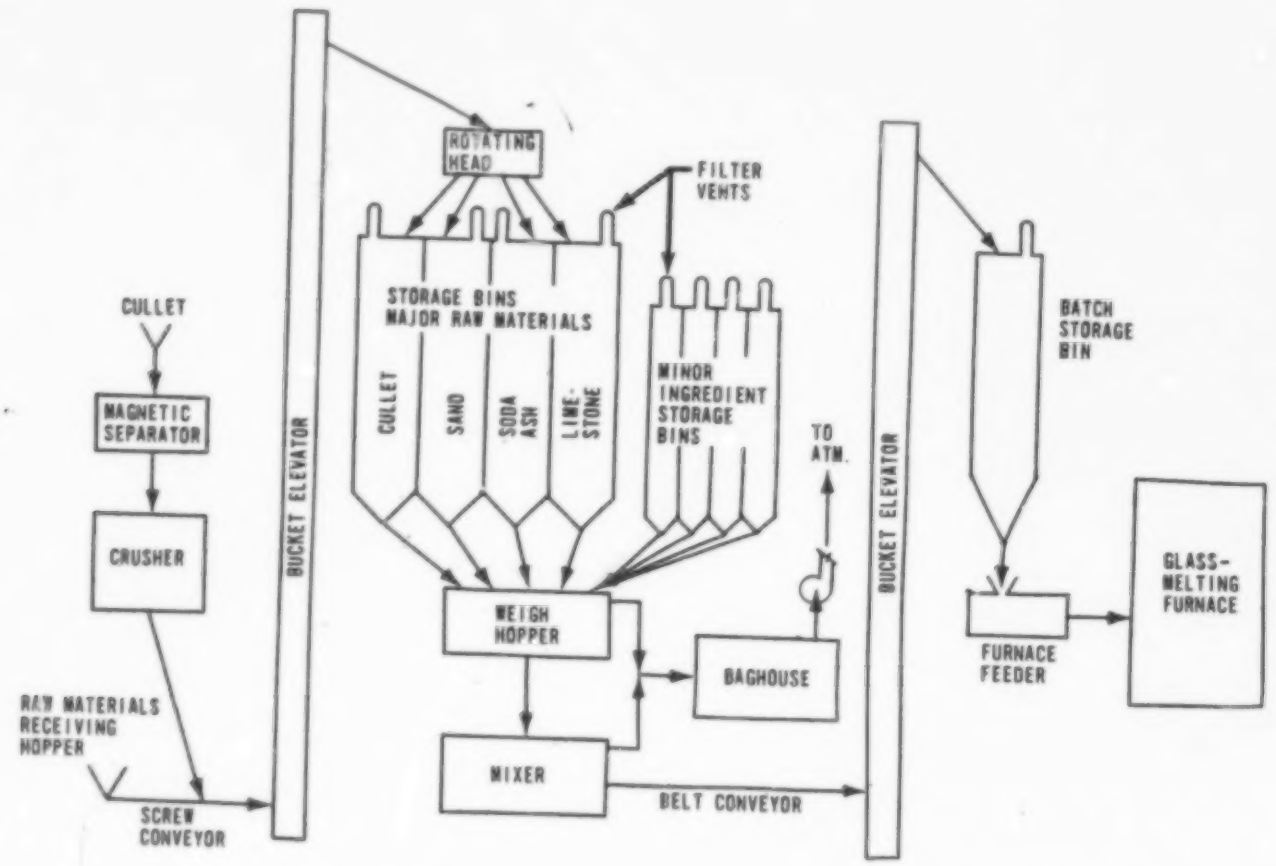


Figure 527. Process flow diagram of a batch plant.

become unnecessary, and relatively small filter vents or dust cabinets can be attached directly to the conveying equipment and storage bins.

On the other hand, exhaust systems are required for ventilating the weigh hoppers and mixers. For example, a 60-cubic-foot-capacity mixer and a 4,500-pound-capacity mixer each require about 600 cfm ventilation air. Seals of polyvinylchloride should be installed between the rotating body of the mixer and its frame to reduce ventilation to a minimum.

Railroad hopper cars and hopper bottom trucks must be connected to sealed receiving hoppers by fabric sleeves so that dust generated in the hoppers during the loading operation is either filtered through the sleeves or exhausted through a baghouse.

Local exhaust systems for dust pickup are designed by using the recommended practice of the Committee on Industrial Ventilation (1960). For example, the ventilation rate at the transfer point between two open belt conveyors is 350 cfm per foot of belt width, with 200 fpm minimum velocity through the hood openings.

AIR POLLUTION CONTROL EQUIPMENT

Because dust emissions contain particles only a few microns in diameter, cyclones and centrifugal scrubbers are not as effective as baghouses or filters are in collecting these small particles; consequently, simple cloth filters and baghouses are used almost exclusively in controlling dust emissions from batch plants.

Filter socks or simple baghouses with intermittent shaking mechanisms are usually designed for a filter velocity of 3 fpm, but baghouses with continuous cleaning devices such as pulse jets or reverse air systems can be designed for filter velocities as high as 10 fpm. Filtration cloths are usually cotton, though nylon, orlon, and dacron are sometimes used. Dusts collected are generally noncorrosive. Filters or baghouses for storage bins are designed to accommodate not only displaced air from the filling operation but also air induced by falling materials. Filtration of air exhaust from pneumatic conveyors used in filling the bins must also be provided. Filters with at least a 1-square-foot area should be mounted on the hand-filled minor-ingredient bins.

Transfer chutes of special design are used for hand filling the minor ingredient bins. They are first attached securely with gaskets to the top of the bins. The bags are dropped into a chute containing knives across the bottom. The knives split the bag, and as the materials fall into the bin, the broken bag seals off the escape of dust from the top of the chute.

GLASS-MELTING FURNACES

While limited quantities of special glasses such as lead or borosilicate are melted in electrically heated pots or in small-batch, regenerative furnaces with capacities up to 10 tons per day, the bulk of production, soda-lime glass, is melted in direct-fired, continuous, regenerative furnaces. Many of these furnaces have added electric induction systems called "boosters" to increase capacity. Continuous, regenerative furnaces usually range in capacity from 50 to 300 tons of glass per day; 100 tons is the most common capacity found in the United States.

Continuous Soda-Lime Glass Furnaces

Continuous, regenerative, tank furnaces differ in design according to the type of glass products manufactured. All have two compartments. In the first compartment, called the melter, the dry ingredients are mixed in correct proportions and are continuously fed onto a molten mass of glass having a temperature near 2,700°F. The dry materials melt after floating a third to one-half of the way across the compartment and disappearing into the surface of a clear, viscous-liquid glass. Glass flows from the melter into the second compartment, commonly referred to as the refiner, where it is mixed for homogeneity and heat conditioned to eliminate bubbles and stones. The temperature is gradually lowered to about 2,200°F. The amount of glass circulating within the melter and refiner is about 10 times the amount withdrawn for production (Sharp, 1954).

Regenerative furnaces for container and tableware manufacture have a submerged opening or throat separating the refiner from the melter. The throat prevents undissolved materials and scum on the surface from entering the refiner. Glass flows from the semicircular refining compartment into long, refractory-lined chambers called forehearths. Oil or gas burners and ventilating dampers accurately control the temperature and viscosity of the glass that is fed from the end of the forehearth to glass-forming machines.

Continuous furnaces for manufacturing rod, tube, and sheet glass differ from furnaces for container and tableware manufacture in that they have no throat between the melter and refiner. The compartments are separated from each other by floating refractory beams riding in a drop arch across the entire width of the furnace. Glass flows from

the rectangular-shaped refiner directly into the forming machines.

Regenerative firing systems for continuous glass furnaces were first devised by Siemens in 1852, and since then, nearly all continuous glass furnaces in the United States have used them. In Europe, continuous glass furnaces employ both recuperative and regenerative systems.

Regenerative firing systems consist of dual chambers filled with brick checkerwork. While the products of combustion from the melter pass through and heat one chamber, combustion air is preheated in the opposite chamber. The functions of each chamber are interchanged during the reverse flow of air and combustion products. Reversals occur every 15 to 20 minutes as required for maximum conservation of heat.

Two basic configurations are used in designing continuous, regenerative furnaces--the end port shown in Figure 528, and the side port in Figure 529. In the side port furnace, combustion products and flames pass in one direction across the melter during one-half of the cycle. The flow is reversed during the other half cycle. The side port design is commonly used in large furnaces with melter areas in excess of 300 square feet (Tooley, 1953).

In the end port configuration, combustion products and flames travel in a horizontal U-shaped path across the surface of the glass within the melter. Fuel and air mix and ignite at one port and discharge through a second port adjacent to the first on the same end wall of the furnace. While the end port design has been used extensively in small-

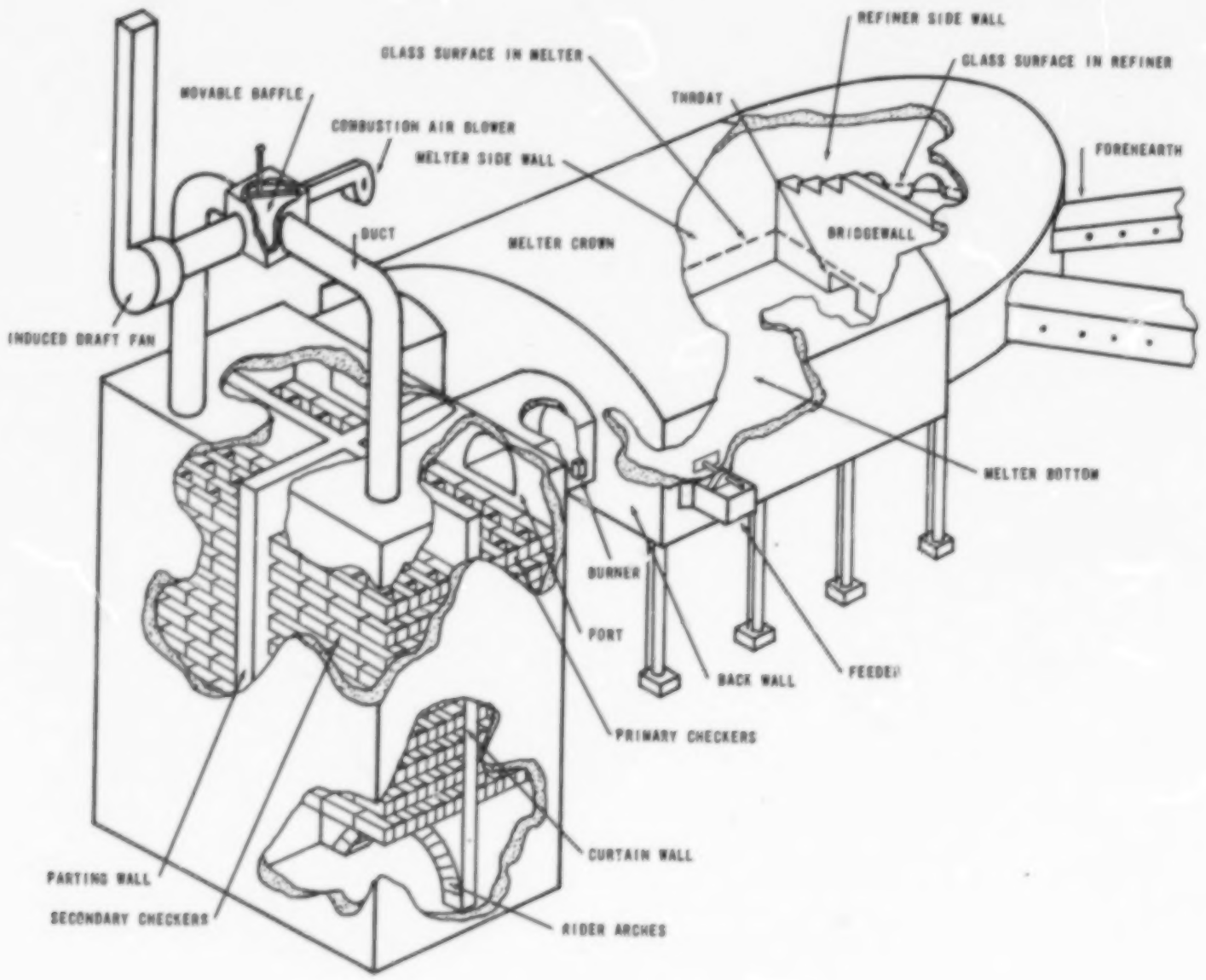


Figure 528. Regenerative end port glass-melting furnace.

er furnaces with melter areas from 50 to 300 square feet, it has also been used in furnaces with melter areas up to 800 square feet.

Continuous furnaces are usually operated slightly above atmospheric pressure within the melter to prevent air induction at the feeders and an overall loss in combustion efficiency. Furnace draft can be produced by several methods: Induced-draft fans, natural-draft stacks, and ejectors.

The Air Pollution Problem

Particulates expelled from the melter are the result of complex physical and chemical reactions that occur during the melting process.

Glass has properties akin to those of crystalline solids, including rigidity, cold flow, and hardness. At the same time, it behaves like a supercooled liquid. It has nondirectional properties, fracture characteristics of an amorphous solid, and no freezing or melting point. To account for the wide range of properties, glass is considered to be a configuration of atoms rather than an aggregate of molecules. Zachariasen (1932) proposed the theory that glass consists of an extended, continuous, three-dimensional network of ions with a certain amount of short-distance-ordered arrangement similar to that of a polyhedral crystal.

These dissimilar properties explain in part why predictions of particulate losses from the melter based solely upon known temperatures and vapor pressures of pure compounds have been inaccurate. Other phenomena affect the generation of particulates. During the melting process, carbon dioxide bubbles and propels particulates from the melting batch. Particulates are entrained by the fast-moving stream of flames and combustion

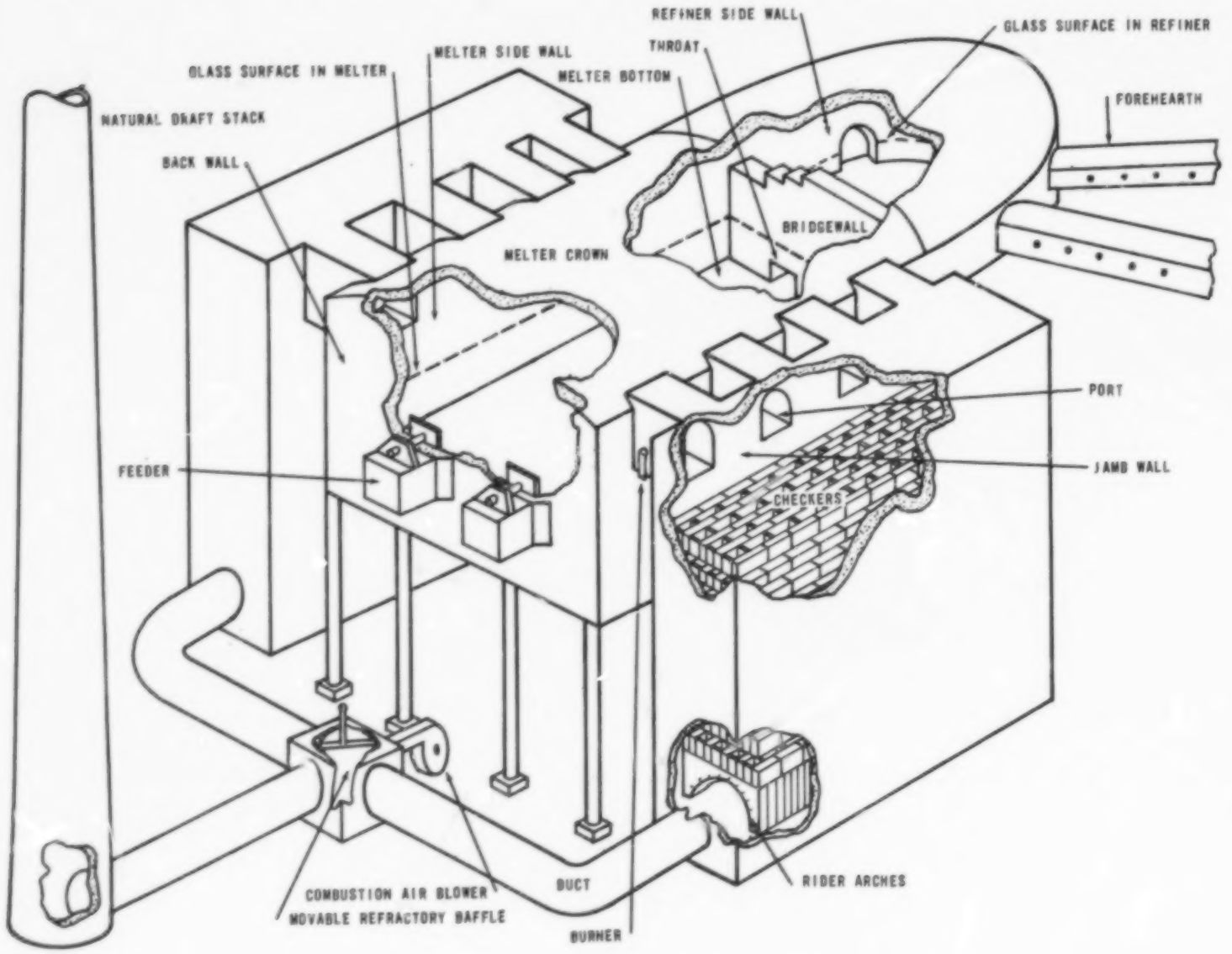


Figure 529. Regenerative side port glass-melting furnace.

gases. As consumption of fuel and refractory temperatures of the furnace increase with glass tonnage, particulates also increase in quantity. Particulates, swept from the melter, are either collected in the checkerwork and gas passages or exhausted to the atmosphere.

Source test data

In a recent study, many source tests of glass furnaces in Los Angeles County were used for determining the major variables influencing stack emissions. As summarized in Table 210, data include: Particulate emissions, opacities, process variables, and furnace design factors. Particle size distribution of two typical stack samples is shown in Table 211. These particulate samples were obtained from the catch of a pilot baghouse venting part of the effluent from a large soda-lime container furnace.

Chemical composition of the particulates was determined by microquantitative methods or by spectrographic analysis. Five separate samples, four from a pilot baghouse, and one from the stack of a soda-lime regenerative furnace, are given in Table 212. They were found to be composed mostly of alkali sulfates although alkalies are reported as oxides. The chemical composition of sample 5 was also checked by X-ray crystallography. In this analysis, the only crystalline material present in identifiable amounts was two polymorphic forms of sodium sulfate.

Opacity of stack emissions

From the source test data available, particulate emissions did not correlate with the opacity of the stack emissions. Some generalizations on opacity can, however, be made. Opacities usu-

Table 210. SOURCE TEST DATA FOR GLASS-MELTING FURNACES

Test No.	Type of furnace[a]	Type of fuel[b]	X_1 (particulate emissions), lb/hr	X_2 (process wt ratio), lb/hr-ft^2 of melter area	X_3, wt fraction of cullet in charge[c]	X_4 (checker volume), ft^3/ft^2 of melter	Maximum opacity of stack emissions, %
C-339b	EP	0-300	7.00	16.7	0.300	5.40	50
C-339	EP	G	3.00	13.8	0.300	5.40	10
C-382-1	EP	G	4.60	16.5	0.300	5.40	10
C-382-2	EP	G	6.40	18.2	0.300	5.40	10
C-536	EP	0-200	4.70	17.5	0.199	5.40	10
C-383	EP	G	8.40	17.9	0.300	6.50	20
Pri Lab	EP	G	3.86	10.9	0.094	8.00	25
Pri Lab	EP	G	4.76	14.6	0.094	8.00	25
Pri Lab	EP	G	4.26	17.1	0.157	8.00	25
Pri Lab	EP	G	6.84	17.4	0.094	8.00	25
Pri Lab	EP	G	4.62	18.5	0.365	9.00	--
Pri Lab	EP	0-300	3.96	14.6	0.269	9.00	45
Pri Lab	EP	G	7.16	20.2	0.175	9.00	20
C-101	EP	G	9.54	15.2	0.300	5.00	20
C-120	EP	G	9.90	14.2	0.320	5.00	20
C-577	SP	0-300	12.70	24.2	0.134	6.90	35
C-278-1	SP	G	3.97	18.3	0.361	6.93	20
C-278-2	SP	0-300	8.44	18.5	0.360	6.93	20
C-653	SP	G	8.90	22.0	0.131	8.74	40
C-244-1	SP	G	6.30	7.5	0.182	7.60	25
C-244-2	SP	G	3.00	5.4	0.100	7.60	25
C-420-1	SP	G	6.30	10.7	0.100	7.60	10
C-420-2	SP	G	6.60	13.2	0.100	7.60	5
C-743	SP	G	10.20	26.2	0.047	8.25	25
C-471	SP	G	6.70	11.6	0.276	5.60	30

[a]EP = end port, regenerative furnace; SP = side port, regenerative furnace.
[b]G = natural gas; 0-200 = U.S. Grade 3 fuel oil; 0-300 = U.S. Grade 5 fuel oil.
[c]Constants: Sulfate content of charge 0.18 to 0.34 wt %.
Fines (-325 mesh) content of charge 0.2 to 0.3 wt %.

ally increase as particulate emissions increase. More often than not, furnaces burning U. S. Grade 5 fuel oil have plumes exceeding 40 percent white opacity while operating at a maximum pull rate, which is the glass industry's common term for production rate. Plumes from these same furnaces were only 15 to 30 percent white opacity while burning natural gas or U. S. Grade 3 (P.S. 200) fuel oil. Somewhat lower opacities may be expected from furnaces with ejector draft systems as compared with furnaces with natural-draft stacks or induced-draft fans.

Hooding and Ventilation Requirements

In order to determine the correct size of air pollution control equipment, the volume of dirty exhaust gas from a furnace must be known. Some of the more important factors affecting exhaust volumes include: Furnace size, pull rate, combustion efficiency, checker volume, and furnace condition.

Exhaust volumes can be determined from fuel requirements for container furnaces given by the formula of Cressey and Lyle (1956).

$$F = [50 + 0.6A] + 4.8T \qquad (137)$$

where

F = total heat, 10^6 Btu/day

A = melter area, ft^2

T = pull rate, tons/day.

This straight-line formula includes minimum heat to sustain an idle condition plus additional

Table 211. SIZE DISTRIBUTION OF PARTICULATE EMISSIONS (MICROMEROGRAPH ANALYSES)

Furnace 1	Flint glass	Furnace 2	Amber glass
Diameter (D), μ	% (by wt) less than D	Diameter (D), μ	% (by wt) less than D
36.60	100	17.40	100
22.00	99.5	15.70	99.8
18.30	98.6	14.00	99.4
16.50	97.7	12.20	96.8
14.60	94.0	11.60	92.5
12.80	84.6	11.00	89.5
12.20	80.7	10.50	87.2
11.60	76.6	9.90	83.4
11.00	72.7	9.30	78.7
10.40	67.7	8.80	75.0
9.80	62.4	8.10	73.4
9.20	58.3	7.00	60.3
8.50	51.8	5.80	47.6
7.30	43.1	4.65	35.6
6.10	34.4	3.49	25.4
4.88	28.0	2.91	20.5
3.66	21.3	2.33	16.4
3.05	18.6	1.74	10.9
2.44	14.9	1.45	8.9
1.83	11.0	1.16	5.3
1.52	8.3		
1.22	4.1		

Table 212. CHEMICAL COMPOSITION OF PARTICULATE EMISSIONS (QUANTITATIVE ANALYSES), METALLIC IONS REPORTED AS OXIDES

Sample source	Baghouse catch	Baghouse catch	Baghouse catch	Baghouse catch	Millipore filter
Test type of glass components	No. 1 amber, wt %	No. 2 flint, wt %	No. 3 amber, wt %	No. 4 flint, wt %	No. 5 flint, wt %
Silica (SiO_2)	0.03	0.3	0.1	4.1	3.3
Calcium oxide (C_aO)	1.70	2.3	0.8	19.2	
Sulfuric anhydride (SO_3)	46.92	25.1	46.7	30.5	39.4
Boric anhydride (B_2O_3)	3.67	1.3			
Arsenic oxide (As_2O_3)	7.71				
Chloride (Cl)	0.01				
Lead oxide (PbO)	0.39				
$K_2O + Na_2O$	29.47	28.1	26.1	36.5	39.2
AL_2O_3		3.5		0.2	
Fluoride		8.6			
Fe_2O_3			0.1	0.6	
MgO				1.4	
ZnO			0.5		
Unknown metallic oxide (R_2O_3)					6.5
Loss on ignition	10.10	30.8	25.7	7.5	11.6

heat for a specified pull rate. Fuel requirements for bridgewall-type, regenerative furnaces are also given by Sharp (1955) and are shown in Figure 530. The melter rating parameter of 4 square feet of melter surface area per daily ton of glass should be used to estimate the fuel requirements of container furnaces at maximum pull rates, but 8 square feet per ton can be used for estimating fuel requirements for non-bridgewall furnaces supplying glass for tableware and for sheet, rod, and tube manufacture. Fuel requirements given are averages for furnaces constructed before 1955; consequently, these furnaces generally require more fuel per ton of glass than do furnaces constructed since 1955. After the fuel requirements are determined, exhaust volumes are computed on the basis of combustion with 40 percent excess combustion air. Forty percent excess combustion air is chosen as representing average combustion conditions near the end of the campaign (a total period of operation without shutting down for repairs to the furnace).

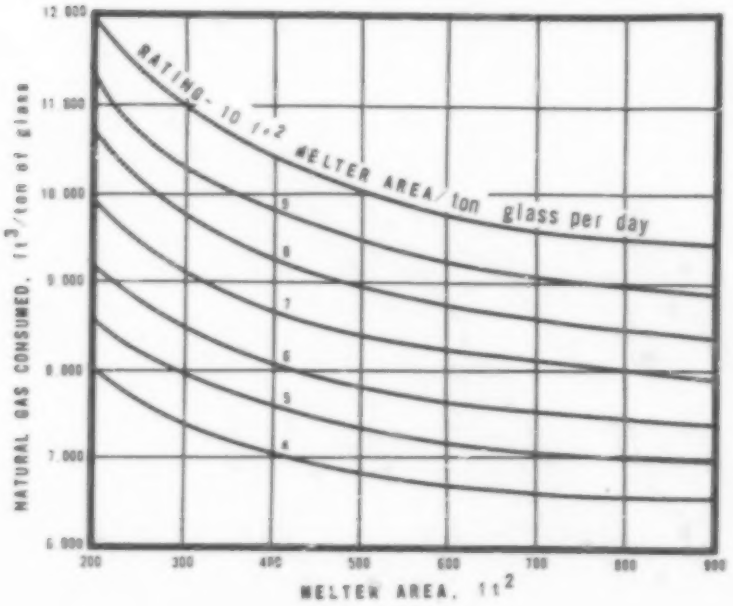


Figure 530. Natural gas for bridgewall-type regenerative furnaces (Sharp, 1955).

Exhaust volumes determined from fuel requirements are for furnaces with induced-draft systems or natural-draft stacks. Exhaust volumes for ejector systems can be estimated by increasing the exhaust volume by 30 to 40 percent to account for ejector air mixed with the furnace effluent.

Exhaust gases from furnaces with natural-draft stacks or induced-draft fan systems usually range in temperature from 600° to 850°F, but exhaust gas temperatures from furnaces containing ejectors are lower and vary from 400° to 600°F. In Table 213 are found chemical analyses of gaseous components of exhaust gases from large, regenerating, gas-fired furnaces melting three kinds of soda-lime glass.

Air Pollution Control Methods

As the furnace campaign progresses, dust carryover speeds destruction of the checkers. Upper courses of the firebrick checker glaze when subjected to high temperatures. Dust and condensate collect on the brick surface and form slag that drips downward into the lower courses where it solidifies at the lower temperature and plugs the checkers. Slag may also act somewhat like flypaper, tenaciously clinging to the upper courses and eventually sealing off upper gas passages.

Hot spots develop around clogged checkers and intensify the destructive forces, which are reflected by a drop in regenerator efficiency and a rise in fuel consumption and horsepower required to overcome additional gas flow resistance through the checkers. Checker damage can finally reach

Table 213. CHEMICAL COMPOSITION OF GASEOUS EMISSIONS FROM GAS-FIRED, REGENERATIVE FURNACES

Gaseous components	Flint glass	Amber glass	Georgia green
Nitrogen, vol %	71.9	81.8	72.5
Oxygen, vol %	9.3	10.2	8.0
Water vapor, vol %	12.4	7.7	12.1
Carbon dioxide, vol %	6.4	8.0	7.4
Carbon monoxide, vol %	0	0.007	0
Sulfur dioxide (SO_2), ppm	0	61	14
Sulfur trioxide (SO_3), ppm	0	12	15
Nitrogen oxides (NO, NO_2), ppm	724	137	NA
Organic acids, ppm	NA[a]	50	NA
Aldehydes, ppm	NA	7	NA

[a]NA = not available.

a point where operation is no longer economical or is physically impossible because of collapse. Thus, successful operation of modern regenerative furnaces requires keeping dust carryover from the melter to an absolute minimum, which also coincides with air pollution control objectives by preventing air contaminants from entering the atmosphere. Aside from reducing air contaminants, benefits derived from reducing dust carryover are many and include longer furnace campaigns, lower maintenance costs, and savings on fuel.

In order to determine which design and operating variables have the greatest effect upon dust carryover and particulate emissions, statistical analysis was performed on source test data previously mentioned in Table 210.

By the method of Brandon (1959), particulate emissions, the dependent variable was found to correlate with the following independent variables and nonquantitative factors:

1. Process weight, lb/hr-ft^2;
2. cullet, wt % of charge;
3. checker volume, ft^3/ft^2 melter;
4. type of furnace, side port or end port;
5. type of fuel, U.S. Grade 5 (PS300) oil or natural gas;
6. melter area, ft^2.

Several simplifying assumptions are made so that furnaces of different sizes can be compared. Process weight per square foot of melter describes a unit process occurring in each furnace regardless of size. Cubic feet of checkers per square foot of melter not only defines the unit's dust-collecting capability but is also a measure of fuel economy. Source tests C-382 and C-536 in Table 210, and other source tests show no appreciable difference in particulate emissions from burning natural gas or U.S. Grade 3 fuel oil.

Correlation of particulate emissions with weight percent sulfate (SO_3) and minus 325-mesh fines in the charge was not possible because of insufficient test data. Limited data available indicate that particulate emissions may double when total sulfate (SO_3) content of the batch charge is increased from 0.3 to 1.0 weight percent. Total sulfates (SO_3) include equivalent amounts of elemental sulfur and all compounds containing sulfur. Sulfates usually comprise over 50 percent of the particulate emissions. They act as fluxing agents preventing the melting dry-batch charge from forming a crust that interferes with heat transfer and melting (Tooley, 1953). Compounds of arsenic, boron, fluorine, and metallic selenium are also expected to be found along with sodium sulfate in the particulate emissions because of their high vapor pressures.

Data roughly indicate that particulate emissions increase severalfold when the quantity of minus 325-mesh fines increases from 0.3 weight percent to 1 or 2 weight percent.

Statistical analysis using the method of curvilinear multiple correlation by Ezekiel (1941) results in the following equation, which describes particulate emissions, the dependent variable, as a function of four independent variables and two nonquantitative independent factors. This equation is valid only when two other independent variables--sulfate content and content of minus 325-mesh fines of the batch--lie between 0.1 to 0.3 weight percent and, also, when fluorine, boron, and lead compounds are either absent from the batch charge or present only in trace amounts.

$$X_1 = a + 0.0226(X_2)^2 - 0.329\,X_2 - 4.412\,X_3 - 0.9379\,X_4 - 0.635\,(X_5)^2 + 6.170\,X_5 \qquad (138)$$

where

X_1 = particulate emissions, lb/hr

X_2 = process wt, lb/hr-ft^2 melter

X_3 = wt fraction of cullet in charge

X_4 = checker volume, ft^3/ft^2 melter

X_5 = melter area, ft^2/100

a = constant involving two nonquantitative independent factors relating the type of furnace (side port or end port) and the type of fuel (U.S. Grade 5 fuel or natural gas).

- a = -0.493 end port - U.S. Grade 5 fuel oil
- a = -0.623 side port - U.S. Grade 5 fuel oil
- a = -1.286 end port - natural gas
- a = -1.416 side port - natural gas.

Particulate emissions computed by this equation for 25 source tests show a standard deviation from measured particulate emissions of $\pm$ 1.4 pounds per hour. Further statistical refinement failed to yield a lower standard deviation.

Emissions to the atmosphere can be predicted by using equation 138 or Figures 531 through 534, which are based upon this equation. The curves should be used only within the limits indicated for the variables. The curves should not be extrapolated in either direction with the expectation of any degree of accuracy, even though they appear as straight lines. Particulate emissions are first determined from Figure 531, then positive or negative corrections obtained from Figures 532 through 534 are added to the emissions obtained from Figure 531.

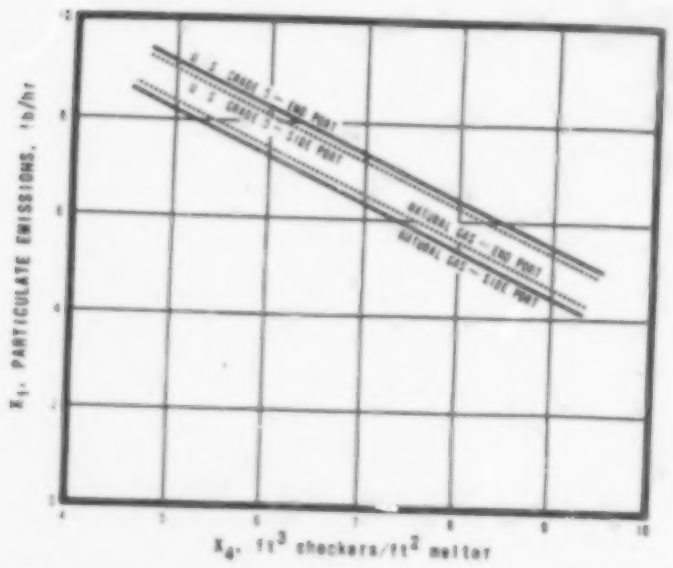

X_1, PARTICULATE EMISSIONS, lb/hr
X_4, ft^3 checkers/ft^2 melter
U. S. GRADE 3 — END PORT
U. S. GRADE 3 — SIDE PORT
NATURAL GAS — END PORT
NATURAL GAS — SIDE PORT

Figure 531. Particulate emissions versus checker volume per ft^2 of melter.

Design and operation of soda-lime, continuous, regenerative furnaces to alleviate dust carryover and minimize particulate emissions are discussed in succeeding paragraphs. Advantages of all-electric, continuous furnaces for melting glass are also cited.

Control of raw materials

Although glassmakers have traditionally sought fine-particle materials for easier melting, these materials have intensified dust carryover in re-

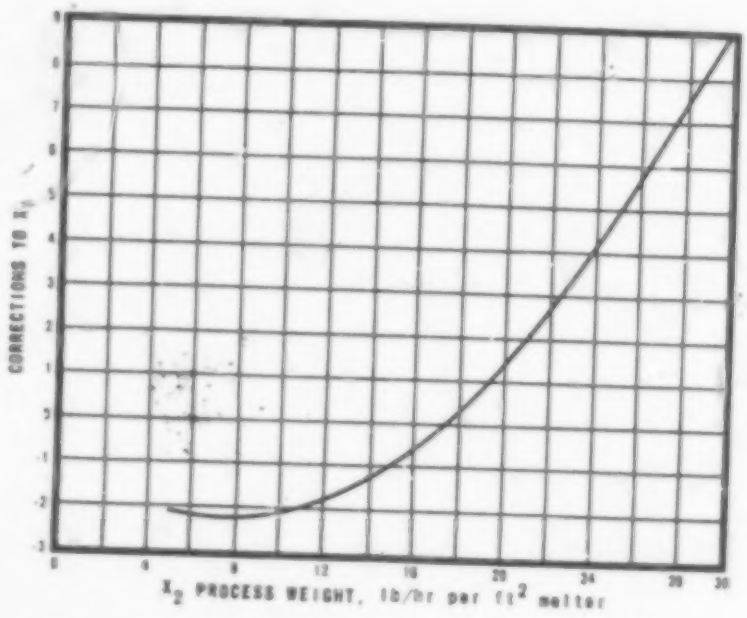


Figure 532. Correction to particulate emissions for process weight per ft^2 melter.

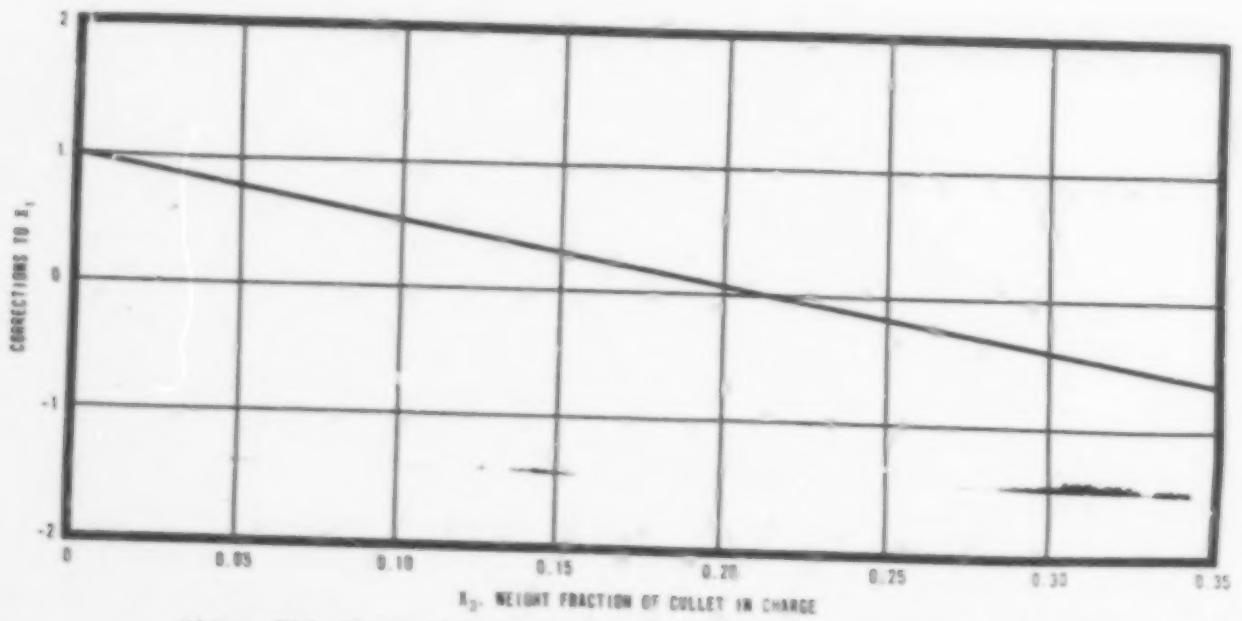


Figure 533. Correction to particulate emissions for cullet content of the batch charge.

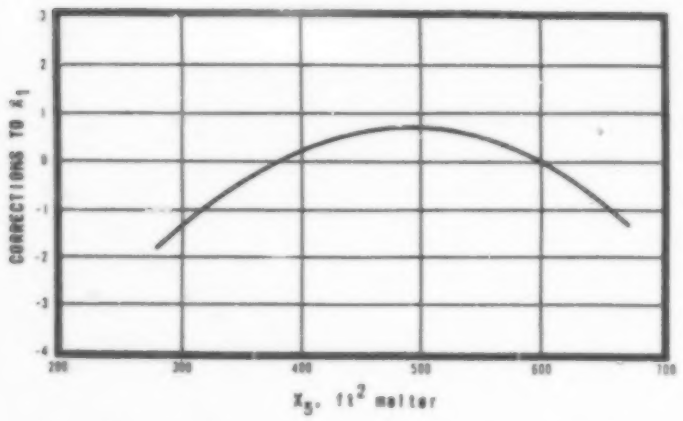


Figure 534. Correction to particulate emissions for melter area.

generative furnaces. A compromise must be reached. Major raw materials should be in the form of small particles, many of them passing U.S. 30-mesh screen, but not more than 0.3 weight percent passing U.S. 325-mesh screen. Because crystals of soda ash, limestone, and other materials may be friable and crush in the mixer, producing excessive amounts of fines, screen analyses of individual raw materials should not be combined for estimating the screen analyses of the batch charge. Crystalline shape and density of raw materials should be thoroughly investigated before raw material suppliers are selected.

Since particulate emissions from soda-lime regenerative furnaces increase with an increase in equivalent sulfate (SO_3) present in the batch charge, sulfate content should be reduced to an absolute minimum consistent with good glassmaking. Preferably, it should be below 0.3 weight percent. Equivalent sulfate (SO_3) content of the batch includes all sulfur compounds and elemental sulfur. Compounds of fluorine, boron, lead, and arsenic are also known to promote dust carryover (Tooley, 1953), but the magnitude of their effect upon emissions is still unknown. In soda-lime glass manufacture, these materials should be eliminated or should be present in only trace amounts.

From the standpoint of suppressing stack emissions, cullet content of the batch charge should be kept as high as possible. Plant economics may, nevertheless, dictate reduction in cullet where fuel or cullet is high in cost or where cullet is in short supply. Some manufacturing plants are able to supply all their cullet requirements from scrap and reject glassware.

Batch preparation

There are a number of ways to condition a batch charge and reduce dust carryover. Some soda-lime glass manufacturers add moisture to the dry batch, but the relative merits of this process are debatable. Moisture is sprayed into the dry-batch charge at the mixer as a solution containing 1 gallon of surface-active wetting agent to 750 gallons of water. Surface tension of the water is reduced by the wetting agent so that the water wets the finest particles and is evenly distributed throughout the batch (Wilson, 1960). Fluxing materials such as salt cake appear more effective, since the unmelted batch does not usually travel so far in the melter tank before it melts. Moisture content of the batch is normally increased to about 2 percent by weight. If the moisture content exceeds 3 percent, batch ingredients adhere to materials-handling equipment and may cake in storage bins or batch cans.

Other batch preparation methods have been employed on a limited-production or experimental basis to reduce dust carryover from soda-ash glass manufacture. One method involves presintering the batch to form cullet and then charging only this cullet to the furnace. Advantages claimed are faster melting, better batch control, less seed formation, reduced clogging in the checkers, and lower stack losses (Arrandale, 1962). A Dutch oven doghouse cover also reduces dust carryover by sintering the top of the floating dry batch before it enters the melter. This method is probably not as efficient as is complete presintering in reducing dust carryover.

Other methods include: (1) Charging briquets, which are made from regular batch ingredients by adding up to 10 percent by weight of water; (2) charging wet batches containing 6 percent moisture, which are made by first dissolving soda-ash to form a saturated solution and mixing this solution with sand and the other dry materials; (3) charging the dry batch (Submerged) in the melter; (4) enclosing batch feeders (Fabrianio, 1961); and (5) installing batch feeders on opposite sides of end port, regenerative furnaces and charging alternately on the side under fire.

Checkers

The design concept of modern regenerative furnaces, with its emphasis on maximum use of fuel, is also indirectly committed to reducing dust carryover. All things being equal, less fuel burned per ton of glass means less dust entrainment by hot combustion gases and flames flowing across the surface of the melting glass. Although container furnaces constructed over 15 years ago required over 7,000 cubic feet of natural gas per ton of glass at maximum pull

rates, container furnaces built today can melt a ton of glass with less than 5,000 cubic feet of natural gas.

While several design changes are responsible for this improvement, one of the most important is the increase in checker volume. The ratio of checker volume, cubic feet per square foot of melter, has been rising during the years from about 5 to 9 today. Enlarged checkers not only reduce fuel consumption and particulate formation but also present a more effective trap for dust particles that are expelled from the melter. Source tests conducted by a large glass-manufacturing company indicated that over 50 percent of the dust carryover from the melter is collected by the checkers and gas passages instead of entering the atmosphere.

Of course, the economics connected with regenerative furnace operation dictates the checker volume. The law of diminishing returns operates where capital outlay for an added volume of checkers will no longer be paid within a specified period by an incremental reduction in fuel costs. Checkers have been designed in double-pass arrangements to recover as much as 55 percent of the heat from the waste gases (Sharp, 1954).

Although dust collects within checkers by mechanisms of impingement and settling, the relationship among various factors influencing dust collection is unknown. These factors include: Gas velocity, brick size, flue spacing, brick setting, and brick composition. Checkers designed for maximum fuel economy may not necessarily have the highest collection efficiency. Further testing will be necessary in order to evaluate checker designs. Checkers designed for maximum heat exchange contain maximum heat transfer surface per unit volume, a condition met only by smaller refractories with tighter spacing. Heat transfer surfaces can be computed by the method given in Trinks (1955). Since gas velocities are also highest for maximum heat transfer, less dust collects by simple settling than by impingement. Dust collection is further complicated in that smaller brick increases the potential for clogging.

To prevent clogging in the checkers and ensure a reasonable level of heat transfer, checkers should be cleaned once per month or more often; an adequate number of access doors should be provided for this purpose (Spain, 1956b). Compressed air, water, or steam may be used to flush fine particles from the checkers. Virtually nothing can be done to remove slag after it has formed. Checkers can be arranged in a double vertical pass to reduce overall furnace height and make cleaning easier. Access doors should also be provided for removing dust deposits from the flues.

Preheaters

Further reductions in fuel consumption to reduce dust emissions may be realized by installing rotary, regenerative air preheaters in series with the checkers. Additional benefits include less checker plugging, reduced maintenance, and increased checker life. Rotating elements of the preheater are constructed of mild steel, low-alloy steel, or ceramic materials. Preheaters raise the temperature of the air to over 1,000°F, and the increased velocity of this preheated air aids in purging dust deposits that block gas passages of the checkers. Exhaust gases passing through the opposite side of the preheater are cooled below 800°F before being exhausted to the atmosphere. A heat balance study of a plate glass, regenerative furnace shows a 9 percent increase in heat use by the installation of a rotary, regenerative air preheater (Waitkus, 1962). To maintain heat transfer and prevent re-entrainment, dust deposits on the preheater elements must be removed by periodic cleaning. Ductwork and valves should be installed for bypassing rotary air preheaters during the cleaning stage.

Refractories and insulation

Slagging of the upper courses of checkerwork can be alleviated in most cases by installing basic (high alumina content) brick in place of superduty firebrick (Robertson et al., 1957). Basic brick courses extend from the top downward to positions where checker temperatures are below 1,500°F. At this temperature, firebrick no longer "wets" and forms slag with dust particles. Dust usually collects in the lower courses of firebrick in the form of fine particles that are easily removed by cleaning. Although basic brick costs 3 or 4 times as much as superduty firebrick, some glass manufacturers are constructing entire checkerworks of basic brick where slagging and clogging are most severe. In some instances, basic refractories are replacing fireclay rider tiles and rider arches in checker supports (Van Dreser, 1962). A word of caution, basic brick is no panacea for all ills of checkers. Chemical composition of the dust should be known, to determine compatibility with the checkers (Fabrianio, 1961).

Regenerative furnaces can be designed to consume less fuel and emit less dust by proper selection and application of insulating refractories. A heat balance study of a side port, regenerative furnace shows that, in the melting process, glass receives 10 percent of heat transfer from convection and 90 percent from radiation. Of the radiation portion of heat transferred, the crown accounts for 33 percent

(Merritt, 1958). Since heat losses through the uninsulated crown can run as high as 10 percent of the total heat input, there is need for insulation at this spot.

Most crowns are constructed of silica brick with a maximum furnace capacity restricted to an operating temperature of 2,850°F (Sharp, 1955). Insulation usually consists of insulating silica brick backed with high-duty plastic refractory. Furnaces are first operated without insulation, so that cracks can be observed. Then the cracks are sealed with silica cement, and the insulation is applied.

Insulation is needed on the melter sidewall and at the port necks to prevent glassy buildup caused by condensation of vapors. Condensate buildup flows across port sills into the melter and can become a major source of stones.

While insulation of sidewalls shows negligible fuel reduction for flint glass manufacture, it does show substantial fuel reduction for colored glasses. The problem in manufacturing colored glass is to maintain a high enough temperature below the surface to speed the solution of stones and prevent stagnation. Insulation on sidewalls raises the mean temperature to a point where stones dissolve and glass circulates freely.

Six inches or more of electrofusion cast block laid over a clay bottom in a bed of mortar (Baque, 1954) not only saves fuel but is also less subject to erosion than is fireclay block.

Insulation is seldom needed on the refining end of the furnace since refiners have become cooling chambers at today's high pull rates. Nose crowns, however, are insulated to minimize condensation and drip (Bailey, 1957). Checkers are sometimes encased in steel to prevent air infiltration through cracks and holes that develop in the refractory regenerator walls during the campaign.

Combustion of fuel

Furnace size also has an effect upon use of fuel, with a corresponding effect on the emissions of dust. Large furnaces are more economical than are small furnaces because the radiating surface or heat loss per unit volume of glass is greater for small furnaces.

Slightly greater fuel economy may be expected from end port furnaces as compared with side port furnaces of equal capacity. Here again, the end port furnace has a heat loss advantage over the side port furnace because it has less exposed exterior surface area for radiating heat. Side port furnaces can, however, be operated at greater percentages in excess of capacity since mixing of fuel with air is more efficient through several smaller inlet ports than it is through only one large inlet port. In fact, end port furnaces are limited in design to the amount of fuel that can be efficiently mixed with air and burned through this one inlet port (Spain, 1955). As far as dust losses are concerned, there are only negligible differences between end port and side port furnaces of equal size. Reduced fuel consumption to reduce dust carryover can also be realized by increasing the depth of the melter to the maximum consistent with good-quality glass. Maximum depths for container furnaces are 42 inches for flint glass (Tooley, 1953) and about 36 inches for amber glass and emerald green glass.

Dust emissions as well as fuel consumption can also be reduced by firing practice. Rapid changes in pull rates are wasteful of fuel and increase stack emissions. Hence, charge rates and glass pull rates for continuous furnaces should remain as constant as possible by balancing loads between the glass-forming machines. If possible, furnaces should be fired on natural gas or U.S. Grade 3 or lighter fuel oil. Particulate emissions increase an average of about 1 pound per hour when U.S. Grade 5 fuel oil is used instead of natural gas or U.S. Grade 3 fuel oil, and opacities may exceed 40 percent white.

Combustion air should be thoroughly mixed with fuel with only enough excess air present to ensure complete combustion without smoke. Excess air robs the furnace of process heat by dilution, and this heat loss must be overcome by burning additional fuel. Volume of the melter should be designed for a maximum fuel heat release of about 13,000 Btu per hour per cubic foot.

Furnace reversals should be performed by an automatic control system to ensure optimum combustion. Only automatic systems can provide the exact timing required for opening and closing the dampers and valves and for coordinating fuel and combustion airflow (Bulcraig and Haigh, 1961). For instance, fuel flow and ignition must be delayed until combustion air travels through the checkers after reversal to mix with fuel at the inlet port to the melter. Furnace reversals are usually performed in fixed periods of 15 to 20 minutes, but an improvement in regenerator efficiency can be realized by programming reversal periods to checker temperatures measured optically. Reversals can then occur when checker temperatures reach preset values consistent with maximum heat transfer (Robertson et al., 1957).

An excellent system for controlling air-to-fuel ratios incorporates continuous flue gas analyzers

for oxygen and combustible hydrocarbons. With this system, the most efficient combustion and best flame shape and coverage occur at optimum oxygen with a trace of combustible hydrocarbons present in the flue gas. Sample gas is cleaned for the analyzers through water-cooled probes containing sprays. The system automatically adjusts to compensate for changes in ambient air density. Fuel savings of 6 to 8 percent can be accomplished on furnaces with analyzers over furnaces not so equipped (Gunsaulus, 1958).

Combustion of natural gas in new furnaces occurs efficiently when the oxygen content of the flue gases in the exhaust ports is less than 2 percent by volume. As the campaign progresses, air infiltration through cracks and pores in the brickwork, air leakage through valves and dampers, increased pressure drop through the regenerators, and other effects combine to make combustion less efficient. To maintain maximum combustion throughout the campaign, pressure checks with draft gages should be run periodically at specified locations (Spain, 1956a). Fuel savings can also be expedited by placing furnace operators on an incentive plan to keep combustion air to a minimum.

Electric melting

Although melting glass by electricity is a more costly process than melting glass by natural gas or fuel oil, melting electrically is a more thermally efficient process since heat can be applied directly to the body of the glass.

Electric induction systems installed on regenerative furnaces are designed to increase maximum pull rates by as much as 50 percent. These systems are called boosters and consist of several water-cooled graphite or molybdenum electrodes equally spaced along the sides of the melter 18 to 32 inches below the surface of the glass. Source test results indicate that pull rates can be increased without any appreciable increase in dust carryover or particulate emissions. Furnace temperatures may also be reduced by boosters, preventing refractory damage at peak operations.

Furnace capacity increase is nearly proportional to the amount of electrical energy expended. A 56-ton-per-day regenerative furnace requires 480 kilowatt-hours in the booster to melt an additional ton of glass, which is close to the theoretical amount of heat needed to melt a ton of glass (Tooley, 1953).

Electric induction can also be used exclusively for melting glass on a large scale. Design of this type of furnace is simplified since regenerative checkerworks and large ductwork are no longer required (Tooley, 1953). One recently constructed 10-ton-per-day, all-electric furnace consists of a simple tank with molybdenum electrodes. A small vent leads directly to the atmosphere, and dust emissions through this vent are very small. The furnace operates with a crown temperature below 600°F and with a thermal efficiency of over 60 percent. Glass quality is excellent, with homogeneity nearly that of optical glass. After the first 11 months of operation, there was no apparent wear on the refractories (Peckham, 1962). First costs and maintenance expenses are substantially lower than for a comparable-size regenerative furnace. An electric furnace may prove competitive with regenerative furnaces in areas with low-cost electrical power.

Baghouses and centrifugal scrubbers

Air pollution control equipment can be installed on regenerative furnaces where particulate emissions or opacities cannot be reduced to required amounts through changes in furnace design, control of raw materials, and operating procedures. Regenerative furnaces may be vented by two types of common industrial control devices--wet centrifugal scrubbers and baghouses.

Figure 535 shows a low-pressure, wet, centrifugal scrubber containing two separate con-

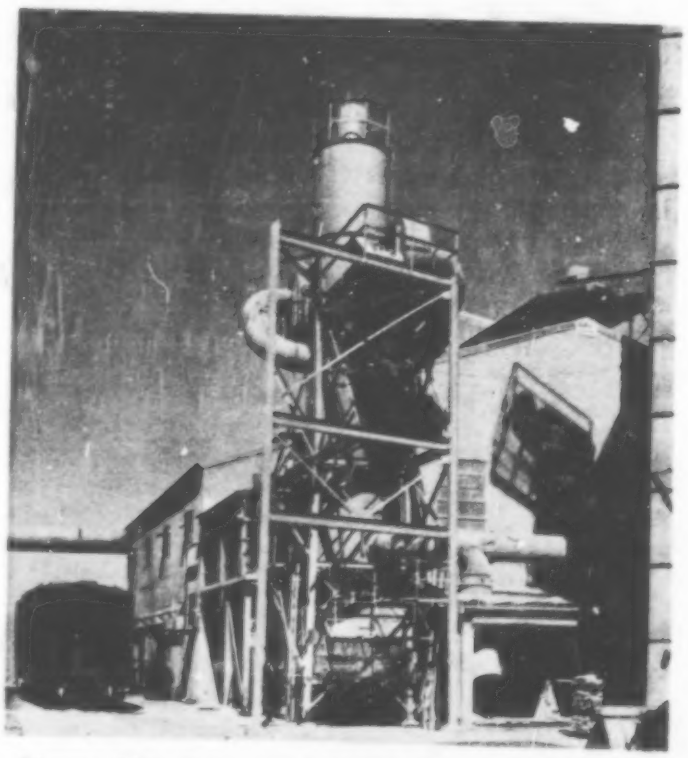


Figure 535. Wet, centrifugal-type scrubber controlling emissions from a glass-melting furnace (Thatcher Glass Co., Sangus, Calif.).

tacting sections within a single casing. Separate 50-horsepower, circulating fans force dirty gas through each section containing two to three impingement elements similar to fixed blades of a turbine. Although the collection efficiency of this device is considered about the highest for its type, source tests show an overall efficiency of only 52 percent. This low efficiency demonstrates the inherent inability of the low-pressure, wet, centrifugal scrubbers to collect particulates of submicron size.

On the other hand, baghouses show collection efficiencies of over 99 percent. Although baghouses have not as yet been installed on large continuous, regenerative furnaces, they have been installed on small regenerative furnaces. One baghouse alternately vents a 1,800-pound- and a 5,000-pound-batch regenerative furnace used for melting optical and special glasses used in scientific instruments. Bags are made of silicone-treated glass fiber. Offgases are tempered by ambient air to reduce the temperature to 400°F, a safe operating temperature for this fabric.

Another baghouse, although no longer in operation, vented a 10-ton-per-day regenerative furnace for melting soda-lime flint glass. Stack gases were cooled to 250°F by radiation and convection from an uninsulated steel duct before entering the baghouse containing orlon bags.

To determine the feasibility of using a cloth filtering device on large continuous, regenerative furnaces, a pilot baghouse was used with bags made of various commercial fabrics. An air-to-gas heat exchanger containing 38 tubes, each 1-1/2 inches in outer diameter by 120 inches in length, cooled furnace exhaust gases before the gases entered the pilot baghouse. The baghouse contained 36 bags, each 6 inches in diameter by 111 inches in length, with a 432-net-square-foot filter area. A 3-horsepower exhaust fan was mounted on the discharge duct of the baghouse.

When subjected to exhaust gases from amber glass manufacture, bags made of cotton, orlon, dynel, and dacron showed rapid deterioration and stiffening. Only orlon and dacron bags appeared in satisfactory condition when controlling dirty gas from flint glass manufacture and when the dirty gas was held well above its dew point. This difference in corrosion between amber and flint glass was found to be caused by the difference in concentrations of sulfur trioxide (SO_3) present in the flue gas.

To reduce the concentration of SO_3 from amber glass manufacture, iron pyrites were substituted for elemental sulfur in the batch, but this change met with no marked success. Stoichiometric amounts of ammonia gas were also injected to remove SO_3 as ammonium sulfate. Ammonia injection not only failed to lessen bag deterioration but also caused the heat exchanger tubes to foul more rapidly.

In all cases, the baghouse temperature had to be kept above the dew point of the furnace effluent to prevent condensation from blinding the bags and promoting rapid chemical attack. At times, the baghouse had to be operated with an inlet temperature as high as 280°F to stay above the elevated dew point caused by the presence of SO_3.

Additional pilot baghouse studies are needed to evaluate orlon and dacron properly for flint glass manufacture. Experiments are also required for evaluating silicone-treated glass fiber bags in controlling exhaust gases from regenerative furnaces melting all types of glass.

Information now available indicates that glass fiber bags can perform at temperatures as high as 500°F, well above the elevated dew points. They are virtually unaffected by relatively large concentrations of SO_2 and SO_3, and there is less danger from condensation. One advantage of glass fiber is that less precooling of exhaust gases is required because of the higher allowable operating temperatures. Reverse air collapse is generally conceded to be the best method of cleaning glass fiber bags, since this material is fragile and easily breaks when regular shakers are installed.

Furnace effluent can be cooled by several methods: Air dilution, radiation cooling columns, air-gas heat exchangers, and water spray chambers. Regardless of the cooling method selected, automatic controls should be installed to ensure proper temperatures during the complete firing cycle. Each cooling method has its advantages and disadvantages. Dilution of offgases with air is the simplest and most troublefree way to reduce temperature but requires the largest baghouse. Air-to-gas heat exchangers and radiation and convection ductwork are subject to rapid fouling from dust in the effluent. Automatic surface-cleaning devices should be provided, or access openings installed for frequent manual cleaning to maintain clean surfaces for adequate heat transfer. If spray chambers are used, severe problems in condensation and temperature control are anticipated.

GLASS-FORMING MACHINES

From ancient times, bottles and tableware were made by handblowing until mechanical production began in the decade preceding the turn of the century with the discovery of the "press and blow"

and the "blow and blow" processes. At first, machines were semiautomatic in operation. Machine feeding was done by hand. Fully automatic machines made their appearance during World War I and completely replaced the semiautomatic machines by 1925. Two types of automatic feeders were developed and are in use today. The first type consists of a device for dipping and evacuating the blank mold in a revolving pot of glass. The second type, called a gob feeder, consists of an orifice in the forehearth combined with shears and gathering chutes (Tooley, 1953).

Glass container-forming machines are of two general types. The first type is a rotating machine in which glass is processed through a sequence of stations involving pressing, blowing, or both. An example of this type of machine is a Lynch machine. A second type is used in conjunction with a gob feeder and consists of independent sections in which each section is a complete manufacturing unit. There is no rotation, and the molds have only to open and close. An example of this type is the Hartford-Empire Individual Section (I.S.) six-section machine shown in Figure 536. Mechanical details and operations of various glass-forming machines for manufacturing containers, flat glass, and tableware are found in the Handbook of Glass Manufacture (Tooley, 1953).

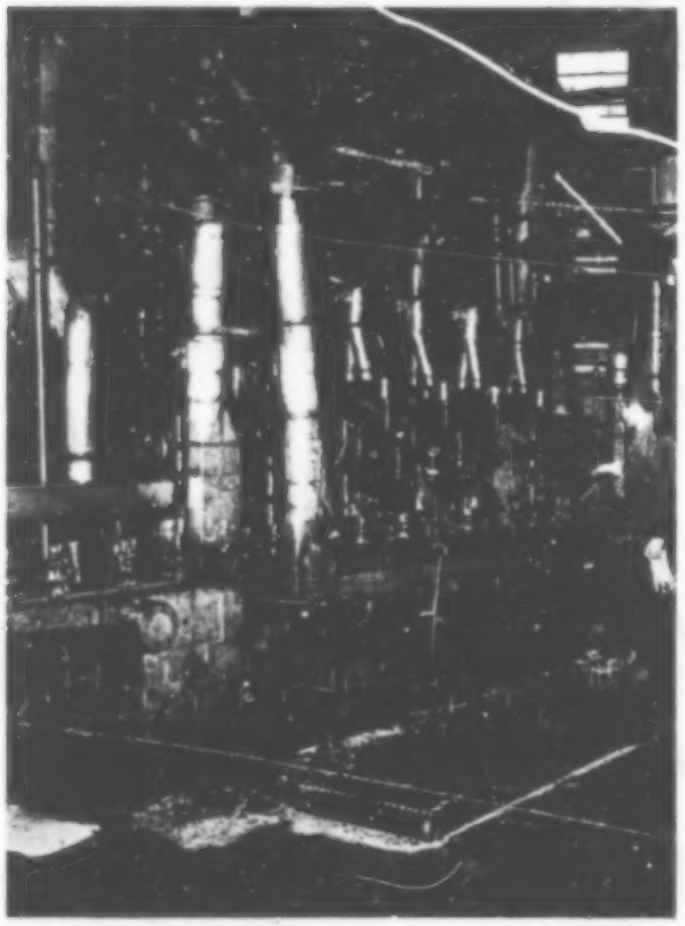


Figure 536. Hartford-Empire I.S. six-section glass-forming machine. (Thatcher Glass Co., Sangus, Calif.).

The Air Pollution Problem

Dense smoke is generated by flash vaporization of hydrocarbon greases and oils from contact lubrication of hot gob shears and gob delivery systems. This smoke emission can exceed 40 percent white opacity.

Molds are lubricated with mixtures of greases and oils and graphite applied to the hot internal surfaces once during 10- to 20-minute periods. This smoke is usually 100 percent white in opacity and exists for 1 or 2 seconds. It rapidly loses its opacity and is completely dissipated within several seconds.

Air Pollution Control Methods

During the past decade, grease and oil lubricants for gob shears and gob delivery systems have been replaced by silicone emulsions and water-soluble oils at ratios of 90 to 150 parts of water to 1 part oil or silicone. The effect has been the virtual elimination of smoke. The emulsions and solutions are applied by intermitten sprays to the delivery system and shears only when the shears are in an opened position.

Lubricating properties of silicone-based emulsions appear in some respects superior to those of soluble oil solutions. Gob drop speeds are increased by 20 to 25 percent. Apparently, the gob rides down the delivery chute on a cushion of steam. Heat from the gob breaks the silicone emulsion, forming an extremely stable resin, a condensation product of siloxane, which acts as a smooth base for the cushioning effect of steam. This resin is degraded in a matter of seconds and must be reformed continuously by reapplying the silicone emulsion.

While graphite gives no apparent advantages to emulsions, a combination of water soluble oil and silicone emulsion appears to be most effective (Singer, 1956). Oil aids the wetting of metal surfaces with silicone and coats metal surfaces, retarding rust formation. Sodium nitrite is also helpful in inhibiting rust when added to silicone emulsion. Water for mixtures must be pure, and in most cases, requires treatment in ion exchangers or demineralizers.

Water treatment is most critical for soluble oil to prevent growth of algae and bacteria. Oil solutions form gelatinous, icicle-like deposits upon drying on the surfaces of pipes and arms of the I.S. ma-

chine. These particles should not be allowed to fall into the mold. Optimum results are obtained by flood lubrication of the delivery system to the maximum amount that can be handled by a runoff wire or blown off by air. Dry lubrication of delivery systems has been tried on an experimental basis by coating the metal contact surfaces with molybdenum disulfide or graphite.

Although future developments in the application of emulsions to molds look promising, present practice still relies upon mixtures of hydrocarbon greases, oils, and graphite. Silicone emulsions and soluble oils eliminate smoke, but several difficulties must be overcome before they can be widely used for mold lubrication. Water emulsions with their high specific heat cause excessive cooling if they are not applied evenly to the mold surfaces by proper atomization. Fine sprays meet with wind resistance, and these sprays cannot be effectively directed to cover the shoulder sections of some molds. Because of the low viscosity of water emulsions, the emulsions are very difficult to meter through existing sight oil feeders. One company has equipped its machine with individual positive-displacement pumps for each nozzle. Invert-post cross-spraying is found to be most effective in giving a uniform coating to the molds of I. S. machines (Bailey, 1957).

Rotating machines are much easier to lubricate than are individual section machines. Emulsion sprays are most effective on rotating machines when mounted at the point of transfer of gobs from the blank mold to the blow mold.

FRIT SMELTERS

INTRODUCTION

Ceramic coatings are generally divided into two classes, depending upon whether they are applied to metal or to glass and pottery. In the case of metal, the coating is widely referred to in this country as porcelain enamel. The use of the term vitreous enamel seems to be preferred in Europe. Glass enamel is sometimes used interchangeably with both terms. On the other hand, the coating applied to glass or pottery is known as ceramic glaze.

Ceramic coatings are essentially water suspensions of ground frit and clay. Frit is prepared by fusing various minerals in a smelter. The molten material is then quenched with air or water. This quenching operation causes the melt to solidify rapidly and shatter into numerous small glass particles, called frit. After a drying process, the frit is finely ground in a ball mill, where other materials are added. When suspended in a solution of water and clay, the resulting mixture is known as a ceramic slip. Enamel slip is applied to metals and fired at high temperatures in a furnace. Glaze slip is applied to pottery or glass and fired in a kiln.

Raw Materials

The raw materials that go into the manufacture of various frits are similar to each other whether the frit is for enameling on steel or aluminum or for glazing. The basic difference is in the chemical composition.

The raw materials used in enamels and glazes may be divided into the following six groups: Refractories, fluxes, opacifiers, colors, floating agents, and electrolytes (Andrews, 1961). The refractories include materials such as quartz, feldspar, and clay, which contribute to the acidic part of the melt and give body to the glass. The fluxes include minerals such as borax, soda ash, cryolite, fluorspar, and litharge, which are basic in character and react with the acidic refractories to form the glass and, moreover, tend to lower the fusion temperatures of the glasses. These refractory and flux materials chiefly comprise the ingredients that go into the raw batch that is charged to the smelter.

Materials falling into the other four groups are introduced later as mill additions and rarely exceed 15 percent of the total frit composition. They include opacifiers, which are compounds added to the glass to give it an opaque appearance such as the characteristic white of porcelain enamels. Examples are tin oxide, antimony oxide, sodium antimonate, and zirconium oxide. The color materials include compounds such as the oxides of cobalt, copper, iron, and nickel. The floating agents consist of clay and gums and are used to suspend the enamel or glaze in water. Electrolytes such as borax, soda ash, magnesium sulfate, and magnesium carbonate are added to flocculate the clay and further aid the clay in keeping the enamel or glaze in suspension (Parmelee, 1951).

Types of Smelters

Smelters used in frit making, whether for enamel or glaze, may be grouped into three classes: Rotary, hearth, and crucible. The rotary smelter is cylindrical and can be rotated in either direction to facilitate fusing, as shown in Figure 537. It can also be tilted vertically for the pouring operation, as demonstrated in Figure 538. The smelter is open at one end for the introduction of fuel and combustion air. It is similarly open at the opposite end for the discharge of flue gases and for charging raw mate-

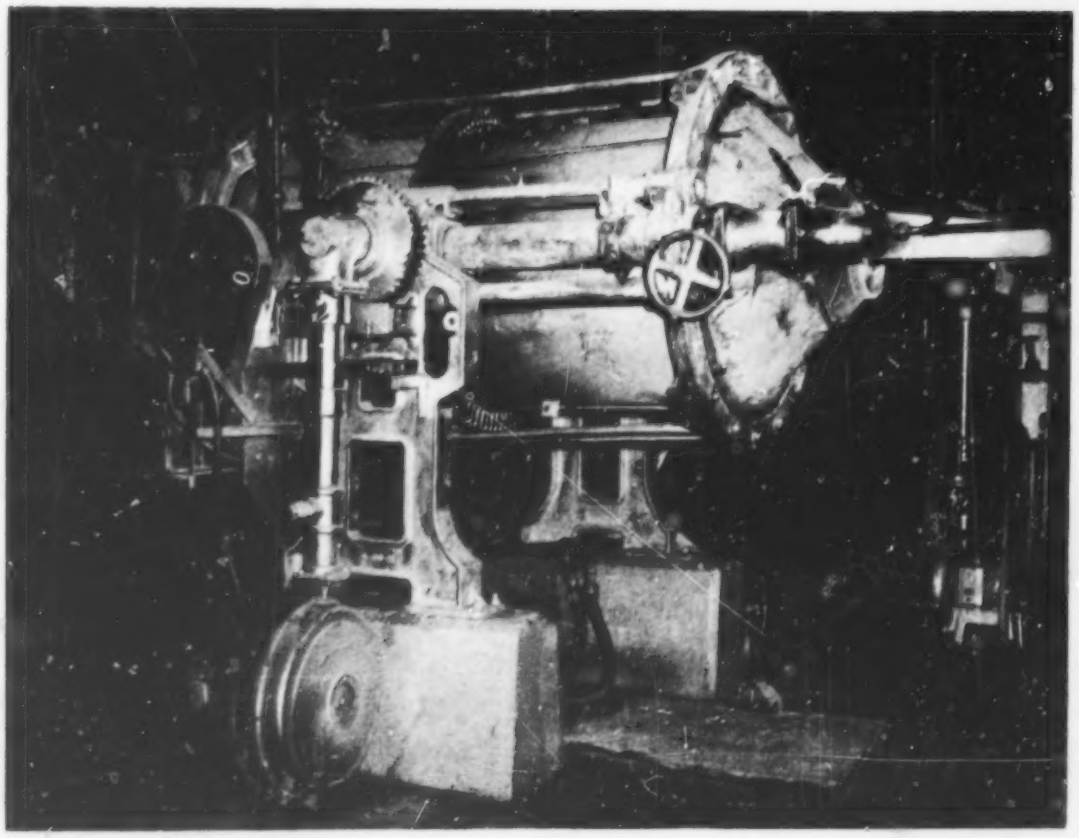


Figure 537. Rotary-type frit smelter (Ferro Corp., Los Angeles, Calif.).

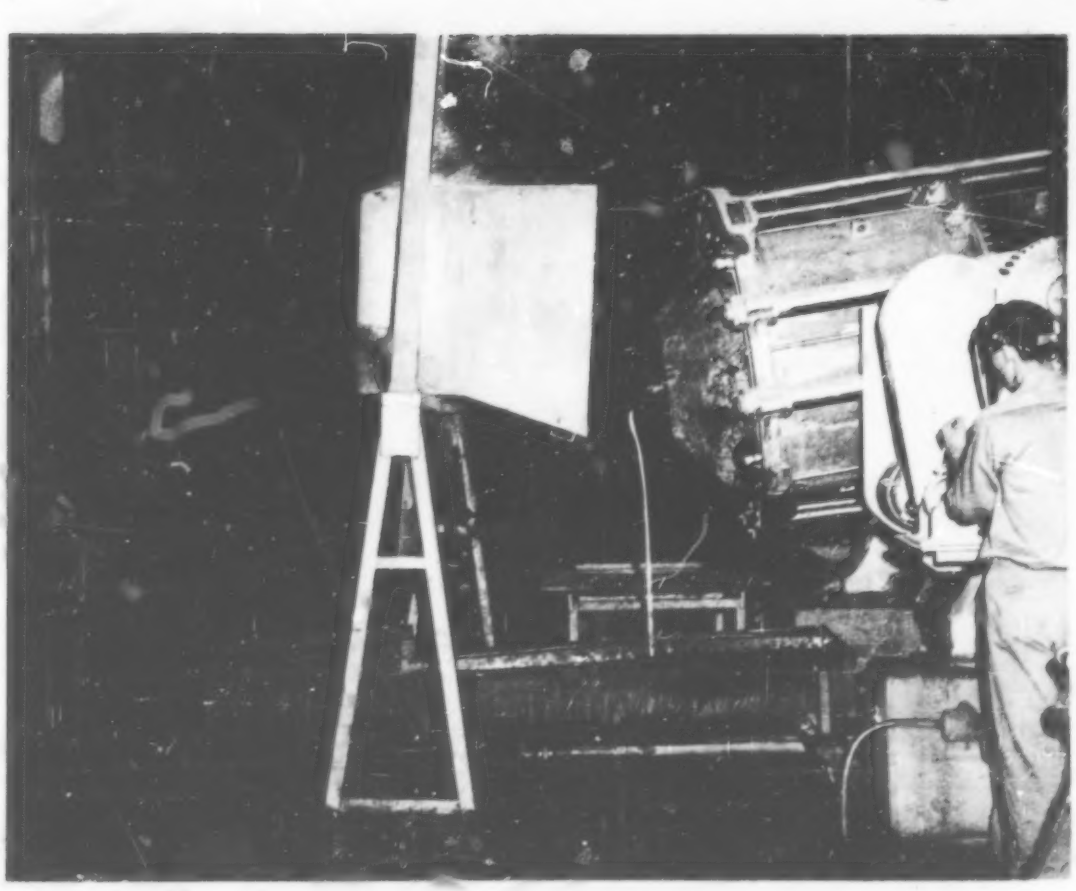


Figure 538. Rotary-type frit smelter in pouring position (Ferro Corp., Los Angeles, Calif.)

rials. Operated solely as a batch-type smelter, it is normally charged by means of a screw conveyor, which is inserted through the opening. Rotary smelters are normally sized to take batches varying from approximately 100 to 3,000 pounds. Fired with either gas or oil, the smelter is lined with high-alumina, refractory firebrick with an average life of from 400 to 600 melts. Firing cycles vary from 1 to 4 hours.

The hearth smelter consists of a brick floor, on which the raw materials are melted, surrounded by a boxlike enclosure. This type of smelter can be either continuous, as illustrated in Figure 539, or batch type, as shown in Figure 540. In either case, the hearth (or bottom) is sloped from one side to a point on the opposite side where the molten material is tapped. The continuous type is usually screw fed. A flue stack is located on the opposite end. Oil or gas is normally used as fuel for the one or more burners. The walls and floor are lined with a first-quality, refractory firebrick. The batch type is sized to take batches ranging from 100 to several thousand pounds. About 30 pounds of batch can be smelted for each square foot of hearth area. The typical continuous-hearth smelter can process 1,000 to 1,500 pounds of raw materials per hour.

The crucible smelter consists of a high-refractory, fireclay, removable crucible mounted within a circular, insulated, steel shell lined with high-grade firebrick, as shown in Figure 541. Heating is usually accomplished with oil or gas burners, though electricity can be used. The combustion chamber surrounds the crucible, occupying the space between the crucible and the shell lining. Because the heat must be transmitted through the crucible to the batch, refractory and fuel costs are high. Crucibles can be sized to smelt a 5-pound batch for laboratory purposes, but the commercial crucibles are sized to take batches from 100 pounds to 3,000 pounds. Smelting cycles vary from 2 to 3 hours at temperatures around 2,200°F, depending upon the size of the batch and its composition. The steel shell is supported by trunnions so that the crucible can be tilted for the pouring operation.

Frit Manufacturing

Since the raw materials that comprise the smelter batch consist of refractories and fluxes, thorough and uniform mixing of these ingredients before the charging operation is essential for efficient smelting. Smelting involves the heating of raw materials until a fairly homogeneous glass is formed. The fundamental changes that occur are interaction of acids and bases, decomposition, fusion, and solution. A considerable quantity of steam is evolved as the borax begins to melt. The order of melting for some of the materials is: Sodium nitrate at 586°F, borax at 1,366°F, soda ash at 1,564°F, litharge at 1,630°F, feldspar at 2,138°F, and quartz at 3,110°F.

If white or light-colored frits are being smelted, smelter refractory linings must be high in alumina and low in iron to prevent discoloration and dark specks in the frit. The batch is protected from contact with fuel gases during the early stages of smelting by the evolution of gases within the smelter. To illustrate, a batch containing 35 percent borax and 10 percent soda ash loses about 165 pounds of water and 42 pounds of carbon dioxide for a 1,000-pound batch of frit. This is equivalent to 483 cfm water vapor and 60 cfm CO_2 at a smelter temperature of 1,700°F and for a smelting period of 30 minutes.

The rate and period of heat application is critical in smelting enamels and glazes. A temperature too low may be sufficient only to vaporize the more fusible materials instead of volatilizing them, and thereby result in a very slow reaction with the more refractory ingredients. A higher operating temperature eliminates this low production rate. If the batch is heated too rapidly, however, the more fusible elements are melted and volatilized before they have a chance to react with the more refractory materials. Driving off the fluxes in this manner results in a harder (less fusible) final batch. Excessive smelting, after the melt is ready to pour, results in a similar condition and, if permitted to continue, necessitates a further increase in temperature to facilitate pouring. Oversmelting also causes loss of opacity, poor gloss, and discoloration in the frit. Insufficient smelting, on the other hand, causes blistering, loss of acid resistance, and poor texture in the finished coating. Batch composition is the determining factor in selecting optimum smelter temperatures and cycles.

After the smelting operation, the molten material is quenched. Rapid cooling can be accomplished with either air, water, or a combination of the two. Air quenching produces a better product but is not normally practiced, owing to the quenching and storage space required. Water quenching is commonly practiced in the industry by pouring the molten material from the tilted smelter into a large pan of water. Water quenching is also frequently done by pouring molten material into a metal trough in which a continuous stream of water is flowing. The trough empties into a large wire basket suspended in a well, which holds the shattered frit but permits the

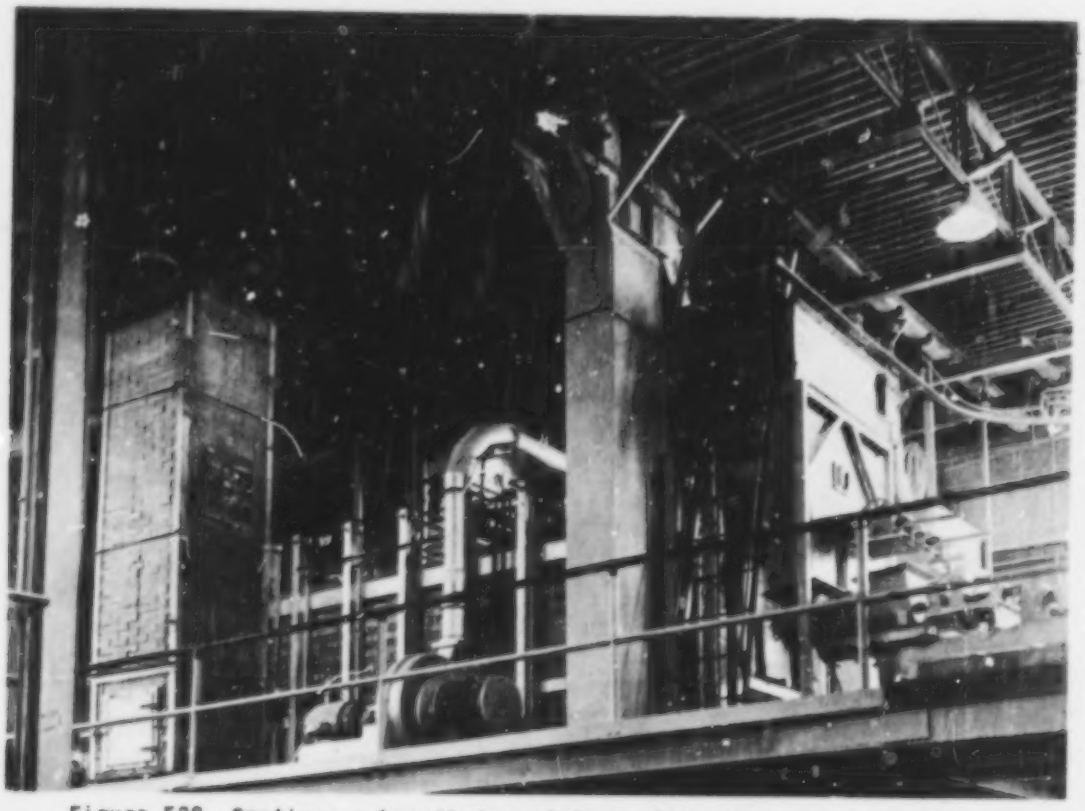


Figure 539. Continuous-hearth-type frit smelter (Ferro Corporation, Los Angeles, Calif.).

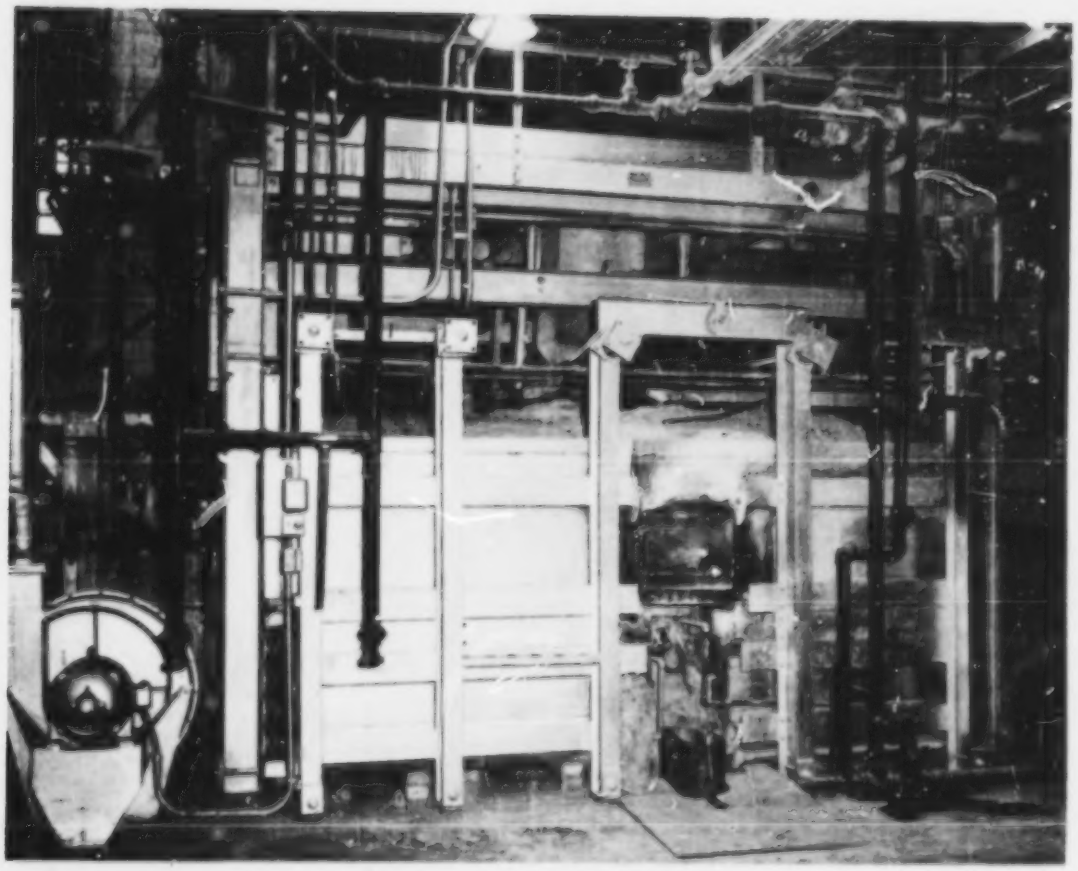


Figure 540. Batch-hearth-type frit smelter (Ferro Corporation, Los Angeles, Calif.).

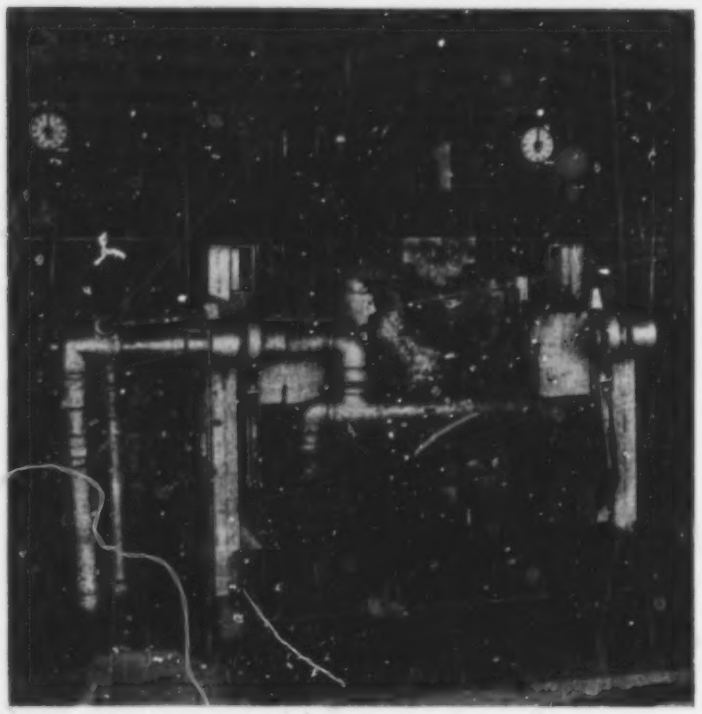


Figure 541. Crucible-type frit smelter (California Metal Enameling Company, Los Angeles, Calif.).

water to flow out through an overflow. Rapid cooling is somewhat impeded by this method owing to a layer of steam that forms over the glass. Air-water quenching appears to be the most economical and effective method since a more thorough shattering of the glass results. In this method the molten material is poured from the smelter and passed through a blast of air and water. Quenching causes the molten material to solidify and shatter into numerous small glass particles (called frit) ranging from 1/4 inch in diameter down to submicron sizes. Its main purpose is to facilitate grinding.

After draining, the frit contains 5 to 15 percent water and may be milled in this condition or may first be dried. Three types of dryers are employed: The drying table, the stationary dryer, and the rotary dryer. The drying table is a flat hearth on which the frit is placed. Heat is applied beneath the hearth, and the frit is raked manually. The stationary dryer consists of a sheet iron chamber in which a basket of frit is placed. Heated air from an exchanger on the smelter flue is passed through the basket of frit. The rotary dryer consists of a porcelain-lined rotating cylinder that is inclined slightly, causing the frit to move through continuously. The typical size is approximately 2 feet in diameter and 20 feet long, though larger cylinders are used. The rotary dryer, which is economical and efficient, can be heated by waste heat or by oil or gas. The frit can be further refined by using magnetic separation to remove small iron particles, which would otherwise cause black specks in the enamel.

The final step in frit making is size reduction, which is normally done with a ball mill. Frits used in porcelain enamel are required to pass a No. 100 sieve (150 μ), though a certain percent of fines must remain as residue on a finer sieve. In the case of ceramic glaze frits, a finer grind is necessary. About one-half of a batch must be less than 2.5 microns with the remainder no greater than 10 microns. Efficient milling is best obtained when the speed of rotation is such that the balls ride three-fourths of the way up one side of the cylinder, and the innermost balls slide back down over the outermost balls. This is achieved, for example, at a speed of 25 rpm for a 4-foot-diameter cylinder. Porcelain balls or flint pebbles are used in the mill. The diameter of the balls ranges from 1 to 3 inches, and the charge should be maintained at about 55 percent of the mill volume. Ball wear amounts to 5 to 10 pounds in milling 1,000 pounds of frit.

Colors, opacifiers, floating agents, and electrolytes are mixed with the frit before it is charged to the ball mill. After the milling operation begins, water is added at a constant rate to keep the specific gravity of the slurry (referred to as slip) at the correct value at all times. After the milling operation, the ceramic slip is screened to remove large particles. A 1- to 2-day aging process then takes place at a temperature close to that at which the enamel or glaze is to be applied. Aging is necessary to set up an equilibrium among the clay, frit, and solution. The enamel or glaze slip is now ready for application.

Application, Firing, and Uses of Enamels

Enamels and glazes may be applied to ware blanks by immersion or spraying (Hansen, 1932). The pouring and brushing methods are seldom employed today. In the dipping operation, the blank is immersed in the slip and then withdrawn and allowed to drain. If the slip is thick, the excess enamel must be shaken from the ware, a process called slushing. Spraying is the application of enamel or glaze slip to ware by atomizing it through an air gun.

After the enamel or glaze has been applied, it must then be burned or fired on the ware to fuse the coating to a smooth, continuous, glassy layer. The firing temperatures and cycles for porcelain enamel on steel and aluminum are approximately 1,500°F (Shreve, 1945) for 5 minutes and 1,000°F for 5 minutes, respectively. Ceramic glaze, however, is fired on pottery at about 2,300°F for several hours or even days.

The firing is accomplished in what is called a furnace in the porcelain enamel industry, and a kiln in the ceramic glaze industry.

Porcelain enamel is used as a protective coating for metals--primarily steel, cast iron, and aluminum. Familiar items are bathtubs, water heater tanks, refrigerators, washing machines, and cooking ranges. Coated aluminum is being used more and more in recent times for signs such as those installed on highways. Ceramic glazes are used as a decorative or protective coating on a wide variety of pottery and glass articles. Examples are lavatory basins, water closets, closet bowls, chinaware, and figurines.

THE AIR POLLUTION PROBLEM

Significant dust and fume emissions are created by the frit-smelting operation. These emissions consist primarily of condensed metallic oxide fumes that have volatilized from the molten charge. They also contain mineral dust carryover and sometimes contain noxious gases such as hydrogen fluoride. In addition, products of combustion, and glass fibers are released. The quantity of these air contaminants can be reduced by following good smelter-operating procedures. This can be accomplished by not rotating the smelter too rapidly, to prevent excessive dust carryover, and by not heating the batch too rapidly or too long, to prevent volatilizing the more fusible elements before they react with the more refractory materials. A typical rotary smelter, for example, discharges to the atmosphere, 10 to 15 pounds of dust and fumes per hour per ton of material charged. In some cases, where ingredients require high melting temperatures (1,500°F or higher), emissions as great as 50 pounds per hour per ton of material have been observed. Depending upon the composition of the batch, a significant visible plume may or may not be present. Tables 214 through 217 indicate the extent of emissions from uncontrolled, rotary frit smelters for various-sized batches and compositions.

HOODING AND VENTILATION REQUIREMENTS

Rotary smelters require a detached canopy-type hood suspended from the lower end of a vertical stack as shown in Figures 537 and 538. It is suspended far enough above the floor to trap the discharge gases from the smelter when in the horizontal position. Refractory-lined, it is of sufficient size to prevent gases from escaping into the room, its size varying with the size of the smelter. The typical hood opening area ranges from 3 to 5 square feet. The stack should be of sufficient height to obtain good draft--about 20 feet--if it is not vented to air pollution control

Table 214. DUST AND FUME DISCHARGE FROM A 1,000-POUND, ROTARY FRIT SMELTER

Test data	Test No.		
	1	2	3
Process wt, lb/hr	174[a]	174[a]	174[a]
Stack vol, scfm	1,390	1,540	1,630
Stack gas temp, °F	450	750	900
Concentration, gr/scf	0.118	0.387	0.381
Stack emissions, lb/hr	1.41	5.11	5.32
CO, vol % (stack condition)	0.002	0.001	0.002
N_2, vol % (stack condition)	76.9	75.10	73.50
	4	5	6
Process wt, lb/hr	292[b]	292[b]	292[b]
Stack vol, scfm	1,310	1,400	1,480
Stack gas temp, °F	960	950	930
Concentration, gr/scf	0.111	0.141	0.124
Stack emissions, lb/hr	1.25	1.79	1.57
CO, vol % (stack condition)	0	0	0
N_2, vol % (stack condition)	73	72.60	73.30

[a]These three tests represent approximately the 1st, 2d, and 3d hours of a 248-minute smelting cycle. The total charge amounted to 717 pounds of material consisting of borax, feldspar, sodium fluoride, soda ash, and zinc oxide.

[b]These three tests represent approximately the 1st, 2d, and 3d hours of a 195-minute smelting cycle. The total charge amounted to 949 pounds of material consisting of litharge, silica, boric acid, feldspar, fluorspar, borax, and zircon.

Table 215. DUST AND FUME DISCHARGE FROM A 3,000-POUND, ROTARY FRIT SMELTER

Test data	Test No.		
	7	8	9
Process wt, lb/hr	472[a]	472[a]	472[a]
Stack vol, scfm	2,240	2,270	2,260
Stack gas temp, °F	630	800	840
Concentration, gr/scf	0.143	0.114	0.172
Stack emissions, lb/hr	2.70	2.20	3.30
CO, vol % (stack condition)	0.02	0.02	0.02
N_2, vol % (stack condition)	75.30	75.60	76.30

[a]These three tests represent approximately the 1st, 2d, and 3d hours of a 248-minute smelting cycle. The total charge amounted to 1,951 pounds of material consisting of litharge, silica, boric acid, feldspar, whiting, borax, and zircon.

Table 216. FLUORIDE DISCHARGE FROM A ROTARY FRIT SMELTER

Test data	Test No.			
	10	11	12	13
Process wt, lb/hr	174[a]	174[a]	162[b]	162[b]
Stack vol, scfm	1,400	1,600	1,000	1,000
Stack gas temp, °F	530	840	480	480
Concentration, gr/scf	0.061	0.035	0.196	0.058
Stack emissions, lb/hr	0.73	0.48	1.68	0.50

[a]These two tests were of 90 minutes' duration each and represented approximately the first half and the second half of a 248-minute smelting cycle. The total charge amounted to 717 pounds of material consisting of borax, feldspar, sodium fluoride, soda ash, and zinc oxide.

[b]These two 60-minute tests represented approximately the 1st and the 4th hours of a 450-minute smelting cycle. The total charge amounted to 1,213 pounds of material consisting of sodium carbonate, calcium carbonate, pyrobar, and silica. The test was specifically conducted for a batch containing maximum carbonates (19%) and no litharge.

Table 217. DUST AND FUME DISCHARGE FROM A 2,000-POUND ROTARY FRIT SMELTER

Test data	Test No.			
	14	15	16	17
Process wt, lb/hr	857[a]	857[a]	890[b]	890[b]
Stack vol, scfm	2,430	2,430	4,347	4,347
Stack gas temp, °F	600	600	340	340
Concentration, gr/scf	0.130	0.112	0.111	0.101
Stack emissions, lb/hr	2.710	2.340	4.150	3.820

[a]These two 60-minute tests represent the 1st and 2d hours of a 140-minute smelting cycle. The total charge amounted to 2,000 pounds of material containing silica, litharge, and whiting.
[b]These two 60-minute tests represent the 1st hour and 37 minutes of a 135-minute smelting cycle. The total charge amounted to 2,000 pounds of material containing silica, litharge, and whiting.

equipment. If it is vented to control equipment, ventilation requirements are approximately 3,000 scfm for a 2,000-pound batch smelter as an example. Hood indraft velocity should be about 500 fpm.

Crucible and hearth smelters do not require hoods but do require a 20- or 25-foot stack to conform with good chimney design practice if not vented to air pollution control equipment. Some crucible smelters are vented directly into the room. If vented to air pollution control equipment, a canopy hood must be used on the crucible smelter. Hood indraft velocities should be approximately 200 fpm. The requirement for a hearth- (box-) type smelter is approximately 4,000 scfm for a 3,000-pound batch smelter. As a general rule, about 70 scfm is required for each square foot of hearth area.

AIR POLLUTION CONTROL EQUIPMENT

The two most feasible control devices for frit smelters are baghouses and venturi water scrubbers. Of these devices, baghouses are more effective. Glass bags cannot be used, however, owing to the occasional presence of fluorides in the effluent. The discharge gases must be cooled by heat exchangers, quench chambers, cooling columns, or by some other device to a temperature compatible with the fabric material selected. Filtering velocities should not exceed 2.5 fpm.

A venturi-type water scrubber is satisfactory if at least 20 to 25 inches of pressure drop is maintained across the venturi throat. The throat velocity should be between 15,000 and 20,000 fpm. The water requirement at the throat is about 6 gpm for each 1,000 cubic feet of gas treated. Power consumption is high owing to the high pressure drop. The venturi scrubber shown in Figure 542 was installed to serve one rotary and two hearth smelters simultaneously. Table 218 includes data indicating the collection efficiency of this scrubber when venting a frit smelter.

A baghouse installation venting four rotary, gas-fired frit smelters is shown in Figure 543. The production capacity of one of the smelters is 3,000 pounds while that of the other three is 1,000 pounds each. Maximum gas temperatures encountered in the discharge stack at a point 20 feet downstream of the smelters are approximately 950°F while the average temperature is 780°F.

Table 218. EFFICIENCY OF VENTURI WATER SCRUBBER ON PARTICULATE MATTER AND FLUORIDES WHEN VENTING THREE FRIT SMELTERS

Test data	Test No.[a]					
	18	19	20	21	22	23
	Dust and fumes			Fluorides		
Process wt, lb/hr	1,360	1,360	1,360	1,360	1,360	1,360
Stack vol, scfm	4,280	4,280	4,280	4,280	4,280	4,280
Stack gas temp, °F	570	552	564	570	552	564
Dust concentration, gr/scf						
Inlet	0.228	0.234	0.127	0.092	0.137	0.034
Outlet	0.074	0.077	0.088	0.006	0.008	0.017
Dust emissions, lb/hr						
Inlet	8.37	8.60	1.78	3.38	5.03	0.48
Outlet	2.72	2.85	1.35	0.22	0.29	0.26
Control efficiency, %	67.50	67.20	30.70	93.20	94	50

[a]Tests No. 18 and 21 represent the first 54 minutes of the 107-minute smelting cycle, tests No. 19 and 22 represent the last 54 minutes, and tests No. 20 and 23 represent the 23-minute tapping period. Total process weight was 3,000 pounds of material consisting of borax, potassium carbonate, potassium nitrate, zinc oxide, titanium oxide, ammonium phosphate, lithium carbonate, sodium silico-fluoride, fluorspar, silica, and talc. Pressure drop across throat was 21 in. WC. Water flow rate to throat was 50 gpm.

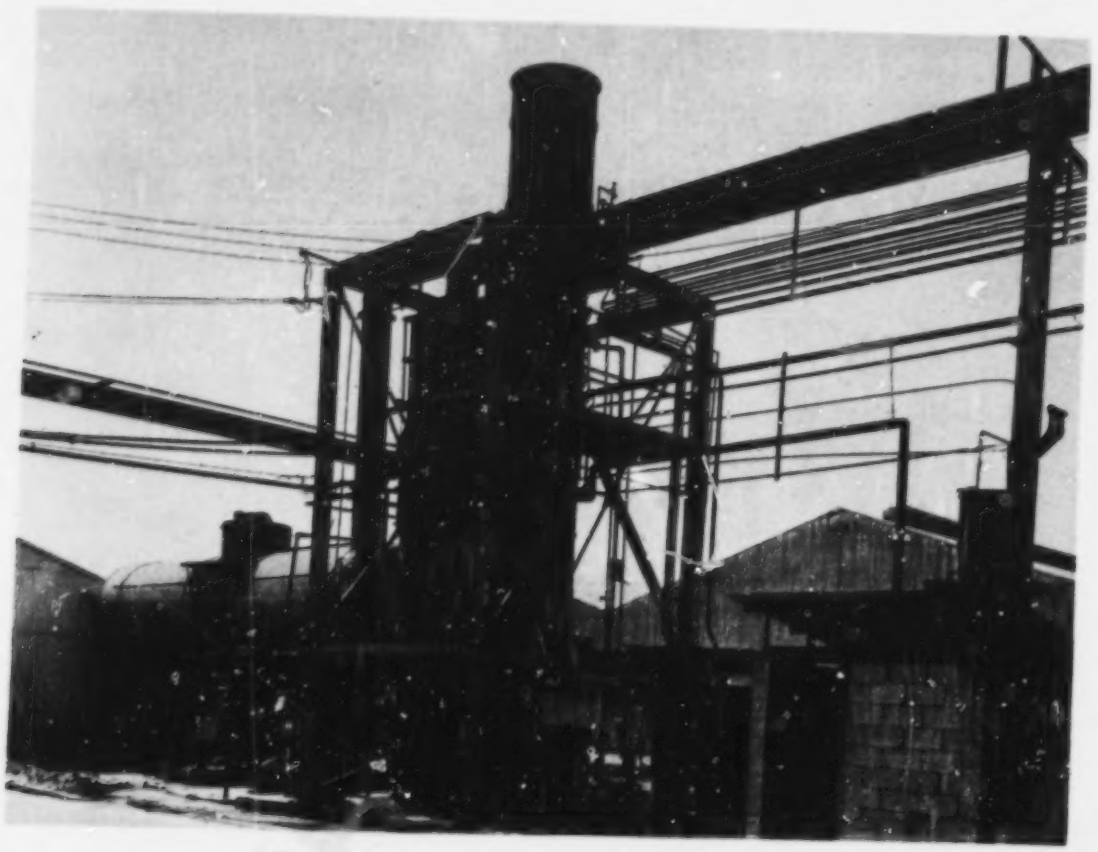


Figure 542. Venturi water scrubber venting three frit smelters (Ferro Corporation, Los Angeles, Calif.).

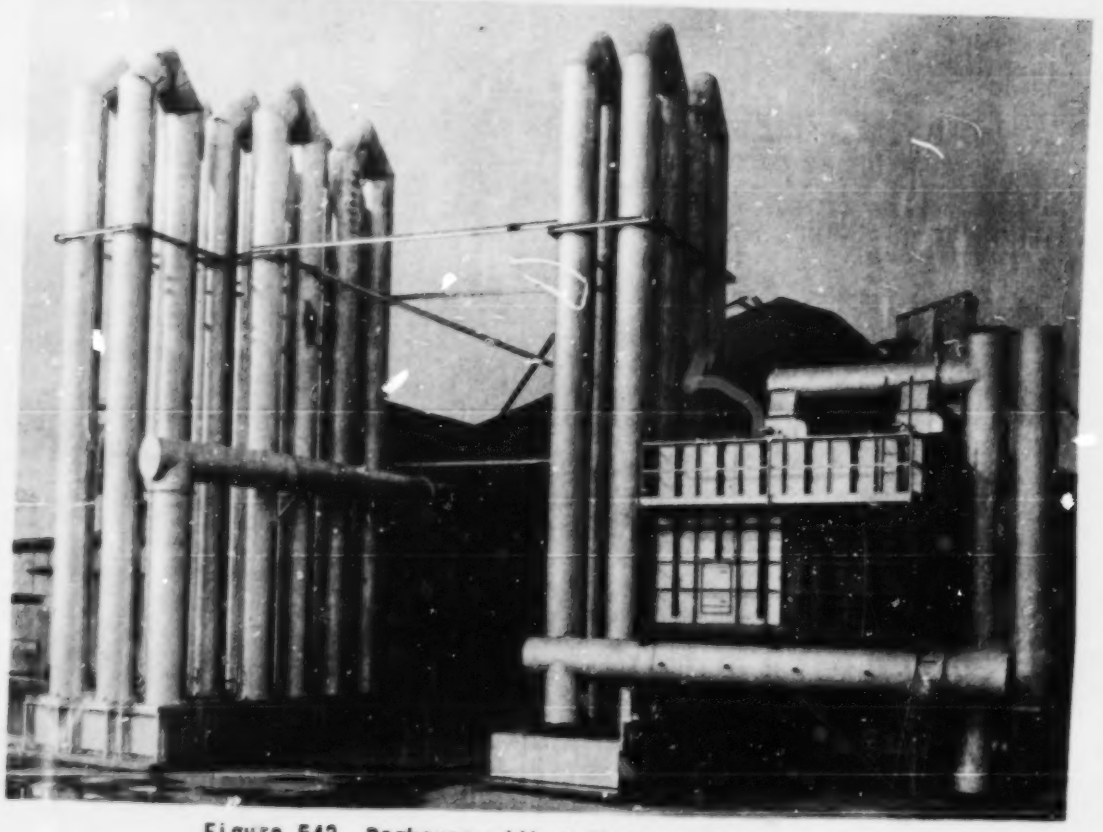


Figure 543. Baghouse with radiant cooling columns venting four rotary frit smelters (Glostex Chemicals, Inc., Vernon, Calif.).

The baghouse is a cloth-tubular, pullthrough type, containing 4,400 square feet of cloth area. It is equipped with an exhaust fan that delivers 9,300 cfm at approximately 170°F. The filtering velocity is 2.2 fpm.

Radiation cooling columns are used to reduce the effluent gas temperature from 585°F at the inlet to the cooling columns to 185°F at the baghouse inlet. Approximately 1,300 lineal feet of 30-inch-diameter, heavy-gage steel duct with a surface area of 10,000 square feet is used. The average overall heat transfer coefficient is 1.35 Btu per hour per square foot per °F, as calculated from actual test data. The cooling columns are not one continuous run, but consist of single, double, and triple runs. Thus, the gas mass velocity varies considerably throughout the unit, with resulting changes in heat transfer coefficients. Additional cooling is accomplished with dilution air at the detached hoods, which are suspended about 1 foot away from the discharge end of each smelter. The baghouse inlet temperature of 185°F is satisfactory for the dacron cloth material used, and excellent bag life can be expected.

FOOD PROCESSING EQUIPMENT

Most foods consumed in the United States today, whether of animal or vegetable origin, are processed to some degree before marketing. Historically, certain foods have been subjected to various preserving processes. More recently we find food purveyors increasingly concerned with processes that render foods more flavorful and easier to prepare. The trend toward greater presale food preparation has possibly caused a shift of at least some air pollutants from many domestic kitchens to a significantly smaller number of food-processing plants.

Food processing includes operations such as slaughtering, smoking, drying, cooking, baking, frying, boiling, dehydrating, hydrogenating, fermenting, distilling, curing, ripening, roasting, broiling, barbecuing, canning, freezing, enriching, and packaging. Some produce large volumes of air contaminants, others, only insignificant amounts. Equipment used to process food is legion. Some of the unit operations involved are the following (Kirk and Othmer, 1947):

Material handling: Conveying, elevating, pumping, packing and shipping.

Separating: Centrifuging, draining, evacuating, filtering, percolating, fitting, pressing, skimming, sorting, and trimming (drying, screening, sifting, and washing fall into this category).

Heat exchanging: Chilling, freezing, and refrigerating; heating, cooking, broiling, roasting, baking, and so forth.

Mixing: Agitating, beating, blending, diffusing, dispersing, emulsifying, homogenizing, kneading, stirring, whipping, working, and so forth.

Disintegrating: Breaking, chipping, chopping, crushing, cutting, grinding, milling, maturating, pulverizing, refining, (as by punching, rolling, and so forth), shredding, slicing, and spraying.

Forming: Casting, extruding, flaking, molding, pelletizing, rolling, shaping, stamping, and die casting.

Coating: Dipping, enrobing, glazing, icing, panning, and so forth.

Decorating: Embossing, imprinting, sugaring, topping, and so forth.

Controlling: Controlling air humidity, temperature, pressure, and velocity; inspecting, measuring, tempering, weighing, and so forth.

Packaging: Capping, closing, filling, labeling, packing, wrapping, and so forth.

Storing: Piling, stacking, warehousing, and so forth.

A description and discussion of each type of equipment used for food processing is not within the scope of this manual. The following discussion will be limited to food processes in which air pollution problems are inherent and in which typical food-processing air contaminants are encountered. This section is not concerned with the production of pet foods or livestock feeds, though in some instances, these materials are byproducts of food processes.

COFFEE PROCESSING

Most coffee is grown in Central and South America. After harvesting and drying at or near the coffee plantation, most "green" coffee beans are exported and further processed before sale to the consumer. Coffee processing in the United States consists essentially of cleaning, roasting, grinding, and packaging.

Roasting is the key operation and produces most of the air contaminants associated with the industry. Roasting reduces the sugar and moisture contents of green coffee and also renders the bulk density of the beans about 50 percent lighter. An apparently desired result is the production of water-soluble degradation products that impart

most of the flavor to the brewed coffee. Roasting also causes the beans to expand and split into halves, releasing small quantities of chaff.

Batch Roasting

The oldest and simplest coffee roasters are direct-fired (usually by natural gas), rotary, cylindrical chambers. These units are designed to handle from 200 to 500 pounds of green beans per 15- to 20-minute cycle and are normally operated at about 400°F. A calculated quantity of water is added at the completion of the roast to quench the beans before discharge from the roaster. After they are dumped, the beans are further cooled with air and run through a "stoner" air classifier to remove metal and other heavy objects before the grinding and packaging. The roaster and cooler and all air-cleaning devices are normally equipped with cyclone separators to remove dust and chaff from exhaust gases. Most present-day coffee roasters are of batch design, though the newer and larger installations tend to favor continuous roasters.

In the batch roaster shown in Figure 544, some of the gases are recirculated. A portion of the gases is bled off at a point between the burner and the roaster. Thus, the burner incinerates combustible contaminants and becomes both an air pollution control device and a heat source for the roaster.

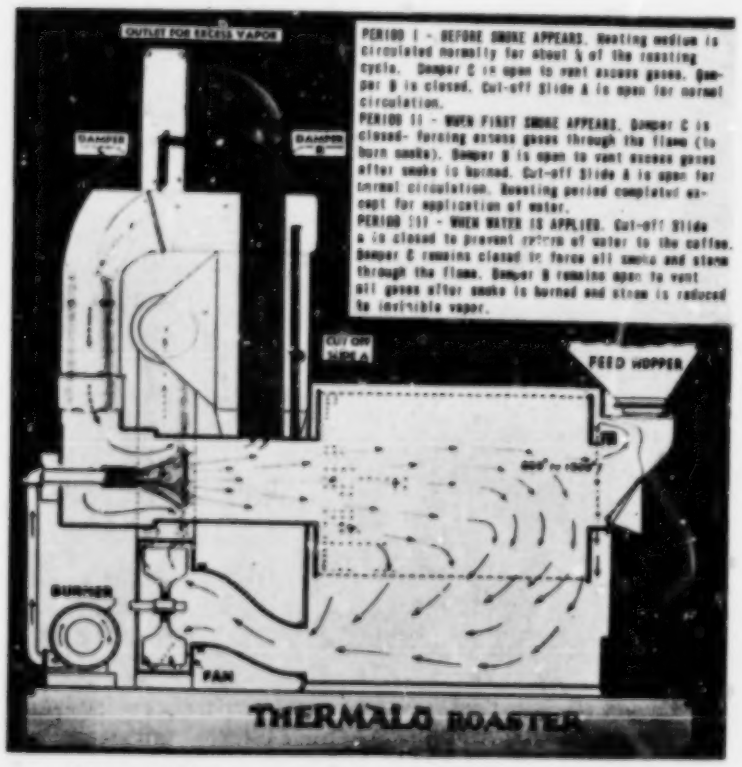

OUTLET FOR EXCESS VAPOR
DAMPER C
DAMPER B
PERIOD I - BEFORE SMOKE APPEARS. Heating medium is circulated normally for about ½ of the roasting cycle. Damper C is open to vent excess gases. Damper B is closed. Cut-off Slide A is open for normal circulation.
PERIOD II - WHEN FIRST SMOKE APPEARS. Damper C is closed- forcing excess gases through the flame (to burn smoke). Damper B is open to vent excess gases after smoke is burned. Cut-off Slide A is open for normal circulation. Roasting period completed except for application of water.
PERIOD III - WHEN WATER IS APPLIED. Cut-off Slide A is closed to prevent return of water to the coffee. Damper C remains closed to force all smoke and steam through the flame. Damper B remains open to vent all gases after smoke is burned and steam is reduced to invisible vapor.
CUT-OFF SLIDE A
FEED HOPPER
BURNER
FAN
THERMALO ROASTER

Figure 544. A recirculating-batch coffee roaster (Jabez Burns - Gump Division, Blaw-Knox Company, New York, N.Y.).

An Integrated Coffee Plant

A process flow sheet of a typical large, integrated coffee plant is shown in Figure 545. Green beans are first run through mechanical cleaning equipment to remove any remaining hulls and foreign matter before the roasting. This system is seen to include a dump tank, scalper, weigh hopper, mixer, and several bins, elevators, and conveyors. Cleaning systems such as this commonly include one or more centrifugal separators from which process air is exhausted.

The direct, gas-fired roasters depicted in Figures 545 and 546 are of continuous rather than batch design. Temperatures of 400°F to 500°F are maintained in the roaster, and the residence time is adjusted by controlling the drum speed. Roaster exhaust products are drawn off through a cyclone separator and afterburner, with some recirculation from the cyclone to the roaster. Chaff and other particulates from the cyclone are fed to a chaff collection system. Hot beans are continuously conveyed through the air cooler and stoner sections. Both the cooler and the stoner are equipped with cyclones to collect particulates.

The equipment following the stoner is used only to blend, grind, and package roasted coffee. Normally, there are no points in these systems where process air is emitted to the atmosphere.

At the plant shown on the flow sheet, chaff is collected from several points and run to a holding bin from which it is fed at a uniform rate to an incinerator. Conveyors in the chaff system may be of almost any type, though pneumatic conveyors are most common. The design of the incinerator depicted is similar to that of the sawdust burners described in Chapter 8 but the incinerator is much smaller.

The Air Pollution Problem

Dust, chaff, coffee bean oils (as mists), smoke, and odors are the principal air contaminants emitted from coffee processing. In addition, combustion contaminants are discharged if chaff is incinerated. Dust is exhausted from several points in the process, while smoke and odors are confined to the roaster, chaff incinerator, and, in some cases, to the cooler.

Coffee chaff is the main source of particulates, but green beans, as received, also contain appreciable quantities of sand and miscellaneous dirt. The major portion of this dirt is removed by air washing in the green coffee-cleaning system. Some chaff (about 1 percent of the green weight) is released from the bean on roasting and

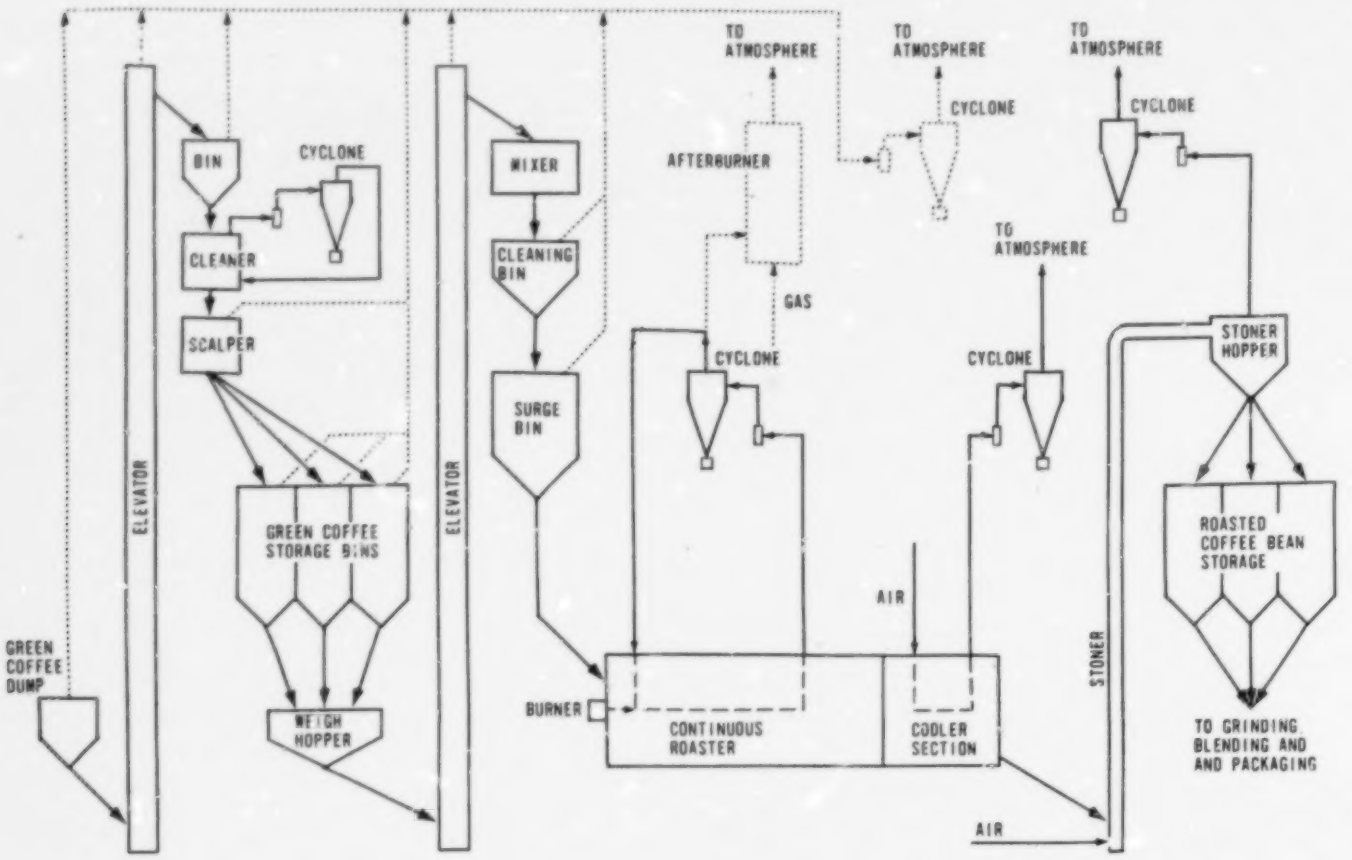


Figure 545. Typical flow sheet for a coffee-roasting plant.

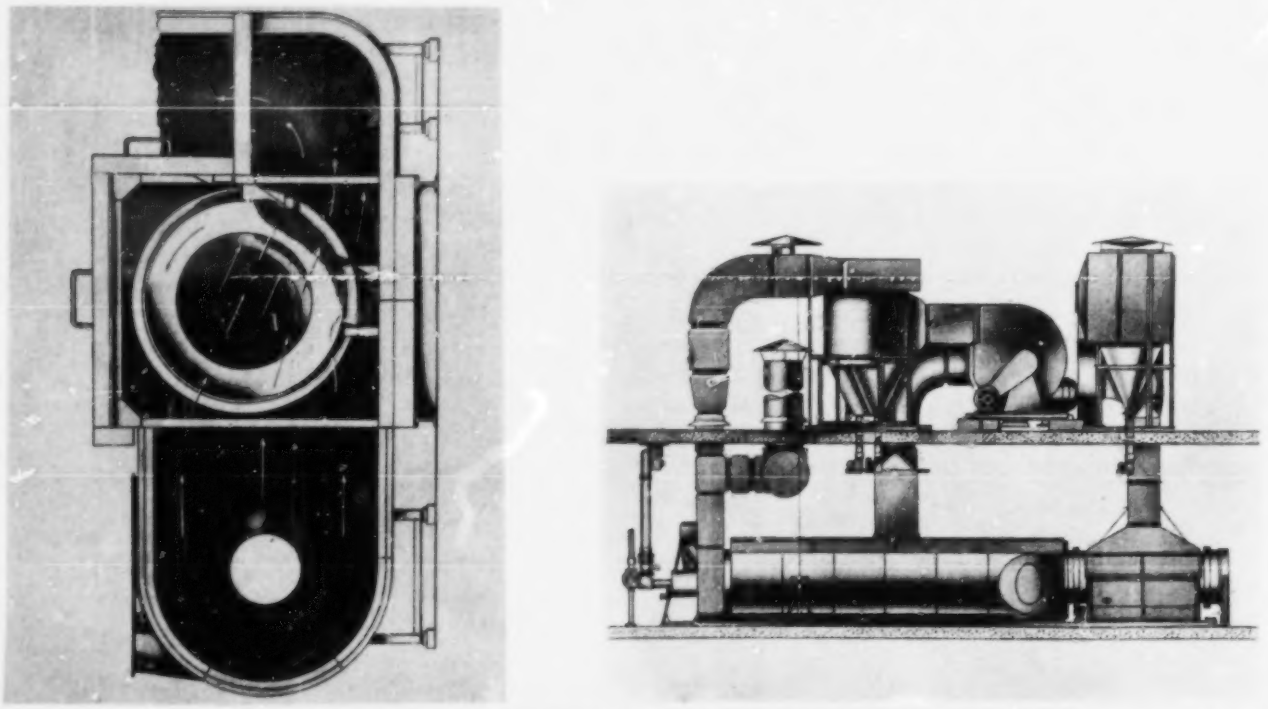


Figure 546. A continuous coffee roaster and cooler:(left) continuous roaster, showing course of the heated gases as they are drawn through the coffee beans in the perforated, helical-flanged cylinder and then into the recirculation system; (right) left-side elevation of continuous roaster, showing relationship of recirculating and cooler fans and the respective collectors on the roof (Jabez Burns - Gump Division, Blaw-Knox Company, New York, N.Y.).

is removed with roaster exhaust gases. A small amount of chaff carries through to the cooler and stoner. After the roasting, coffee chaff is light and flaky, particle sizes usually exceeding 100 microns. As shown in Table 219, particulate-matter emissions from coffee processing are well below the limits permitted by typical dust and fume prohibitions.

Table 219. ANALYSIS OF COFFEE ROASTER EXHAUST GASES

	Contaminant concentration		
	Continuous roaster		Batch roaster
	Roaster	Cooler	
Particulate matter, gr/scf	0.189	0.006	0.160
Aldehydes (as formaldehyde), ppm	139	--	42
Organic acids (as acetic acid), ppm	223	--	175
Oxides of nitrogen (as NO_2), ppm	26.8	--	21.4

Coffee roaster odors are attributed to alcohols, aldehydes, organic acids, and nitrogen and sulfur compounds, which are all probably breakdown products of sugars and oils. Roasted coffee odors are considered pleasant by many people, and indeed, they may often be pleasant under certain conditions. Nevertheless, continual exposure to uncontrolled roaster exhaust gases usually elicits widespread complaints from adjacent residents. The pleasant aroma of a short sniff apparently develops into an annoyance upon long exposure.

Visible bluish-white smoke emissions from coffee roasters are caused by distilled oils and organic breakdown products. The moisture content of green coffee is only 6 to 14 percent, and thus there is not sufficient water vapor in the 400°F to 500°F exhaust gases to form a visible steam plume. From uncontrolled, continuous roasters, the opacity of exhaust gases exceeds 40 percent almost continuously. From batch roasters, exhaust opacities normally exceed 40 percent only during the last 10 to 15 minutes of a 20-minute roast. Smoke opacity appears to be a function of the oil content, the more oily coffee producing the heavier smoke. The water quenching of batch-roasted coffee causes visible steam emissions that seldom persist longer than 30 seconds per batch.

Hooding and Ventilation Requirements

Exhaust volumes from coffee-processing systems do not vary greatly from one plant to another insofar as roasting, cooling, and stoning are concerned. Roasters equipped with gas recirculation systems exhaust about 24 scf per pound of finished coffee. Volumes from nonrecirculation roasters average about 40 scf per pound. A 10,000-pound-per-hour, continuous roaster with a recirculation system exhausts about 4,000 scfm. A 500-pound-per-batch, nonrecirculation roaster exhausts about 1,000 scfm. Each batch cycle lasts about 20 minutes.

Coolers of the continuous type exhaust about 120 scf per pound of coffee. Batch-type coolers are operated at ratios of about 10 scfm per pound. The time required for batch cooling varies somewhat with the operator. Batch-cooling requirements are inversely related to the degree of water quenching employed.

Continuous-type stoners use about 40 scf air per pound of coffee. Batch-stoning processes require from 4 to 10 scfm per pound, depending upon ductwork size and batch time.

Air Pollution Control Equipment

Air contaminants from coffee-processing plants have been successfully controlled with afterburners and cyclone separators, and combinations thereof. Incineration is necessary only with roaster exhaust gases. There is little smoke in other coffee plant exit gas streams where only dust collectors are required to comply with air pollution control regulations.

Separate afterburners are preferable to the combination heater-incinerator of the batch roaster shown in Figure 544. When the afterburner serves as the roaster's heat source, its maximum operating temperature is limited to about 1,000°F. A temperature of 1,200°F or greater is necessary to provide good particulate incineration and odor removal.

A roaster afterburner should always be preceded by an efficient cyclone separator in which most of the particulates are removed. A residence time of 0.3 second is sufficient to incinerate most vapors and small-diameter particles at 1,200°F. Higher temperatures and longer residences are, however, required to burn large-diameter, solid particles. Afterburner design is discussed in Chapter 5.

Properly designed centrifugal separators are required on essentially all process airstreams up to and including the stoner and chaff collection system. With the plant shown, cyclones are required at the roaster, cooler, stoner, chaff storage bin, and chaff incinerator. In addition, the scalper is a centrifugal classifier venting process air. Some plants also vent the

green coffee dump tank and several conveyors and elevators to centrifugal dust collectors.

For best results the chaff incinerator should be of the design discussed in Chapter 8 in which combustible material is fed at a uniform rate. It is, however, considerably smaller and has burning rates usually below 100 pounds per hour.

The inorganic ash content of the chaff, at approximately 5 percent by weight, is considerably greater than that of most combustible refuse fed to incinerators. Provisions should be made in the incinerator design so that this material does not become entrained in the exhaust gases. If most of the noncombustible material is discharged with products of combustion from the incinerator, the combustion contaminants then exceed 0.3 grain per cubic foot calculated to 12 percent carbon dioxide.

SMOKEHOUSES

Smoking has been used for centuries to preserve meat and fish products. Modern smoking operations do not differ greatly from those used by our forefathers, though the prime purposes of smoking today appear to be the imparting of flavor, color, and "customer appeal" to the food product. Curing and storage processes have been improved to the point where preservation is no longer the principal objective.

The vast majority of smoked products are meats of porcine and bovine origin. Some fish and poultry and, in rare instances, vegetable products are also smoked as gourmet items.

The Smoking Process

Smoking is a diffusion process in which food products are exposed to an atmosphere of hardwood smoke. Table 220 lists an analysis of smoke produced through the destructive distillation of a hardwood. As smoke is circulated over the food, aldehydes, organic acids, and other organics are adsorbed onto its outer surface. Smoking usually darkens the food's natural color, and in some cases, glazes the outer surface.

Regardless of smokehouse design, some spent gases are always exhausted to the atmosphere. These contain odorous, eye-irritating gases and finely divided, organic particulates, often in sufficient concentration to exceed local opacity restrictions.

Smokehouses are also used to cook and dry food products either before or after smoking. Air contaminants emitted during cooking and drying are normally well below allowable control limits.

Table 220. ANALYSIS OF WOOD SMOKE USED IN MEAT SMOKEHOUSES
(Jensen, 1945)

Contaminant	Concentration, ppm
Formaldehyde	20 to 40
Higher aldehydes	140 to 180
Formic acid	90 to 125
Acetic and higher acids	460 to 500
Phenols	20 to 30
Ketones	190 to 200
Resins	1,000

Atmospheric Smokehouses

The oldest smokehouses are of atmospheric or natural-draft design. These boxlike structures are usually heated directly with natural gas or wood. Smoke is often generated by heating sawdust on a steel plate. These smoke generators are normally heated with natural gas pipe burners located in the bottom of the house. Hot, smoky gases are allowed to rise by natural convection through racks of meat. Large atmospheric houses are often built with two or three levels of meat racks. One or more stacks are provided to exhaust spent gases at the top of the house. In some instances the vents are equipped with exhaust fans. During the smoking and drying cycles, exhaust gas temperatures range from 120° to 150°F. Slightly higher temperatures are sometimes encountered during the cooking cycle.

Recirculating Smokehouses

Most large, modern, production meat smokehouses are of the recirculating type (Figure 547) wherein smoke is circulated at reasonably high velocities over the surface of the product. The purpose is to provide faster and more nearly uniform diffusion of organics onto the product, and more uniform temperatures throughout the house. These units are usually of stainless steel construction and are heated by steam or gas. Smoke is piped to the house from external smoke generators. Each unit is equipped with a large circulating fan and, in some instances, a smaller exhaust fan. During smoking and cooking, exhaust volumes of 1 to 4 cfm per square foot of floor area are maintained. The exhaust rate is increased to 5 to 10 cfm per square foot during the drying cycle. Recirculating smokehouses are usually equipped with temperature and humidity controls, and the opacity and makeup of exhaust gas are usually more constant than those from atmospheric units.

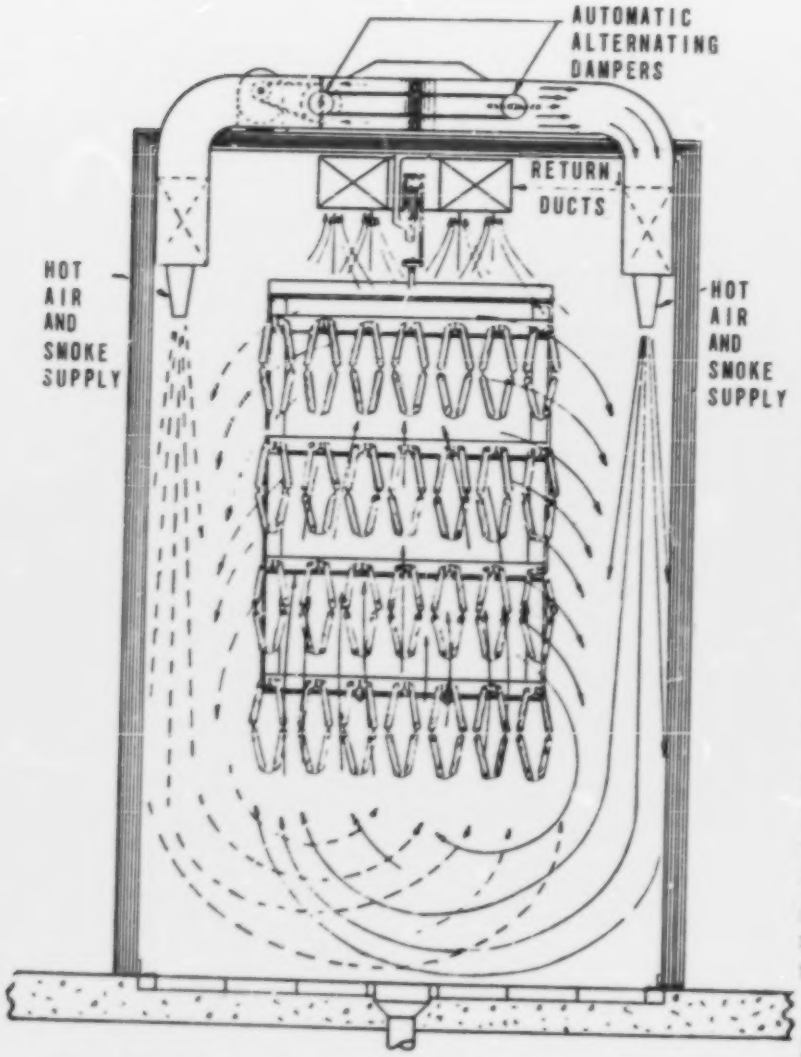


Figure 547. A modern recirculating smokehouse (Atmos Corp., Chicago, Ill.).

The Air Pollution Problem

Smokehouse exhaust products include organic gases, liquids, and solids, all of which must be considered air contaminants. Many of the gaseous compounds are irritating to the eyes and reasonably odorous. A large portion of the particulates is in the submicron size range where light scattering is maximum. These air contaminants are attributable to smoke, that is, to smoke generated from hardwood, rather than from the cooked product itself.

Exhaust gases from both atmospheric and recirculating smokehouses can be periodically expected to exceed 40 percent opacity, the maximum allowable under many local air pollution control regulations. With the possible exception of public nuisance, smokehouse exhaust gases are not likely to exceed other local air quality standards. As shown in Table 220, concentrations of particulate matter average only 0.14 grain per scf.

Hooding and Ventilation Requirements

Atmospheric smokehouses are designed with exhaust volumes of about 3 cubic feet per square foot of floor area. Somewhat higher volumes are used with atmospheric houses of two or more stories. Inasmuch as there are no air recirculation and normally little provision for forced draft, the exhaust rate for an atmospheric house is essentially constant over the drying, cooking, and smoking cycles. Moreover, there is often some smoke in the house even during the cooking and drying cycles. This is particularly true where smoke is generated in the house rather than in an external smoke generator. If gases are to be ducted to air pollution control equipment, an exhaust fan should be employed to offset the added pressure drop. When an afterburner is used, it can often be positioned to provide additional natural draft.

Recirculation smokehouses have a considerably wider range of exhaust rates. During smoking and cooking cycles, volumes of 1 to 4 cubic feet per square foot of floor area are exhausted. The rate increases to 5 to 10 cubic feet per square foot during the drying cycle. Recirculation houses are almost always equipped with external smoke generators, and a control of smoke flow is much more positive. There is essentially no smoke in the houses during the cooking and drying cycles.

Most smokehouses do not require hooding. Exhaust gases are normally ducted directly to the atmosphere or to control equipment. Some atmospheric houses are, however, equipped with hoods over the loading doors to gather smoke that might escape during the shifting of meat racks. The latter situation is due to the inherently poor distribution of smoke and heat in an atmospheric house. To maintain product uniformity, the meat racks must often be shifted while there is smoke in the house. Most atmospheric houses do not have exhaust systems adequate to prevent appreciable smoke emissions from the door during these instances. Hoods and exhaust systems are sometimes installed principally for worker comfort. The hoods or fans, or both, may be located in corridor ceilings immediately above the doors. These ventilators are often operated automatically whenever the doors are opened. Volumes can be appreciable, in some instances exceeding the smokehouse's exhaust rate.

There are normally no appreciable smoke emissions from doors of recirculation-type smokehouses. Temperature and smoke distribution are sufficient so that there is no need to shift meat in the houses. Moreover, the doors are designed to provide tighter closures. Recircula-

tion houses are operated under positive pressure, and any small opening causes large emissions of smoke.

Bypassing control devices during nonsmoking periods

Many operators of recirculation smokehouses find it desirable to bypass air pollution control devices during nonsmoking periods. From the standpoint of air pollution control, this practice is not unreasonable. The major smokehouse air contaminant is smoke. Concentrations of air contaminants during cooking and drying are relatively small, comparable to those of ordinary meat-cooking ovens. Drying-cycle exhaust gases are 2 to 4 times more voluminous than those vented during the smoking cycle. The size of control equipment is materially increased if drying gases are ducted to it. The initial cost and operating cost of a smokehouse's air pollution control system can, therefore, be considerably reduced if exhaust gases are bypassed during drying and cooking cycles when no smoke is introduced into the house.

If houses are to be bypassed during nonsmoking periods, the ductwork and valving should be designed to provide automatic or nearly automatic operation. Water seal dampers (Figure 548) are preferable. Mechanical dampers demand optimum maintenance for satisfactory closure. They are considerably more likely to malfunction owing to corrosion and contamination with greases and tars. Moreover, mechanical dampers are more susceptible to physical damage than water dampers are. Ideally, damper operation should be keyed to other smokehouse auxiliaries such as fans and smoke generators. Where controls are manually operated, there is a strong possibility that dampers will not be opened or closed at proper times, causing either overloading of the control device or the discharge of untreated air contaminants directly to the atmosphere.

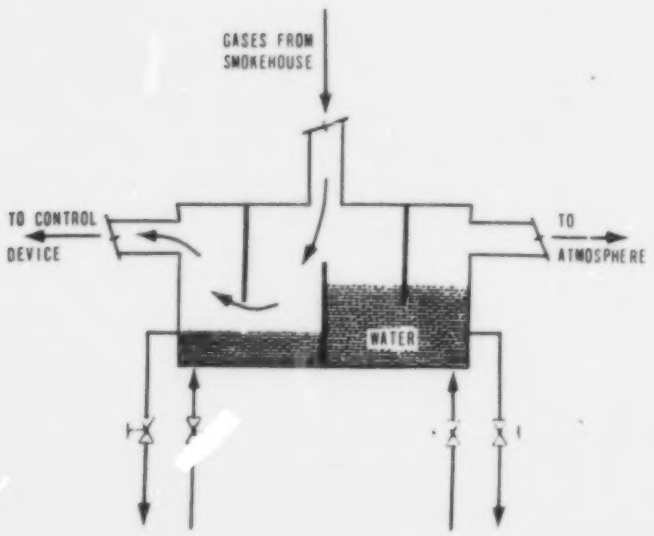


Figure 548. Diagram of a water-operated damper used to bypass the air pollution control device during nonsmoking periods.

Air Pollution Control Equipment

Afterburners

Smoke, odors, eye irritants, and organic particulate matter can be controlled with afterburners, provided temperature and design are adequate. Most of these contaminants can be eliminated at temperatures of 1,000°F to 1,200°F in well-designed units. Larger diameter particulate matter is somewhat more difficult to burn at these temperatures; however, since concentrations of particulate matter from smokehouses are reasonably small, this limitation is not critical.

Electrical precipitators

Low-voltage, two-stage electrical precipitators were installed in the Los Angeles area as early as 1957 to control visible smokehouse air contaminants. They have since been used at many other locations in the United States. Before 1957, their use had been confined principally to air-conditioning applications.

Electrical precipitators are, of course, effective only in the collection of particulate matter. They cannot be used to control gases or vapors. At smokehouse installations, their purpose is to collect the submicron smoke particles responsible for visible opacity. Two-stage precipitators have been shown capable of reducing smoke opacities to less than 10 percent under ideal conditions.

A typical two-stage precipitator control system with a wet, centrifugal collector is shown in Figure 549. The wet collector is used to control temperature and humidity and also remove a small amount of particulates. This is followed by a heater in which gas temperatures are regulated before the gases enter the ionizer. Voltages of 6,000 to 15,000 volts are applied to the ionizer and plate sections. Particulate matter collects on the plates and drains, as a gummy liquid, to the collection pan below.

For satisfactory control of visible emissions, it has been found that superficial gas velocities through the plate collector section should not exceed 100 fpm. Some difficulty has been experienced owing to channeling in the collector. For best operation, vanes or other means of ensuring uniform flow should be used ahead of the plate section.

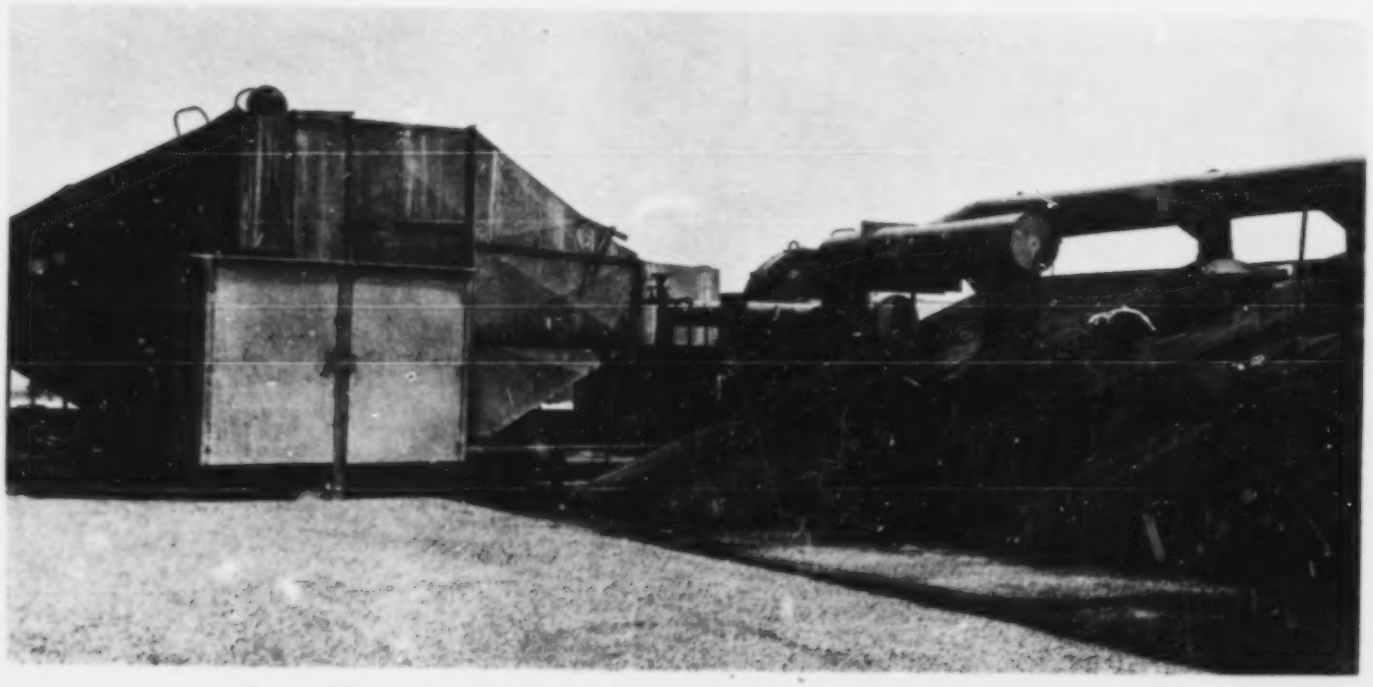


Figure 549. A two-stage precipitator and wet centrifugal collector venting smokehouses (The Rath Packing Co., Vernon, Calif.).

Even under optimum conditions, a slight trace of smoke can be expected from the precipitator's outlet. At the discharge of the unit, eye irritation is usually severe, and odors are strong though not overpowering. These odors and eye irritants can constitute a public nuisance, depending upon plant location.

Electrical precipitation versus incineration

Both electrical precipitation and incineration offer the classical choice of high initial cost versus high operating cost, but in addition, they differ markedly from the standpoint of air pollution control.

Electrical precipitators are capable of collecting particulate matter and thereby reducing visible emissions to tolerable amounts. They have no effect on nitrogen oxides and little effect, if any, on gaseous eye irritants and odors. If arcing occurs, some small and probably insignificant quantity of ozone is also produced. The initial cost of precipitators is high, and their operating cost low in comparison with that of afterburners. Smokehouse precipitators do, however, require a relatively high degree of maintenance. If they are not properly maintained, poor control efficiency and fire damage are probable. Fire damage can result in extended outage periods during which uncontrolled exhaust gases may vent directly to the atmosphere.

Incineration is much more effective than electrical precipitation is in controlling gaseous organics and finely divided particulates. Large particles are, however, relatively difficult to burn at the normal operating temperatures and residence times of smokehouse afterburners. Under average conditions, collection efficiency for particulate matter (about 65 percent) is roughly the same as that of a two-stage electrical precipitator. Fuel costs make the operation of an incineration device more expensive than that of a precipitator. Nevertheless, maintenance is much less a problem. There is no buildup of tars and resins in the afterburner or stack to impede its operation. As with any smokehouse control device, tars accumulate in the ductwork between the house and afterburner, necessitating periodic cleaning. As shown in Table 221, incineration creates additional nitrogen oxides, increasing concentrations from about 4 ppm to approximately 12 ppm on the average.

Comparative test data on smokehouse afterburners and electrical precipitators, as shown in Tables 221 and 222, indicate that collection efficiencies for particulate matter, aldehydes, and organic acids are of the same magnitude for both types of control dequipment. These data fail to reflect larger concentrations of odors and eye irritants from electrical precipitators that are readily apparent upon personal inspection of the devices.

Table 221. ANALYSES OF MEAT SMOKEHOUSE EXHAUST GASES BEFORE AND AFTER INCINERATION IN NATURAL GAS-FIRED AFTERBURNERS

	Contaminant concentration				Control efficiency, %
	Smokehouse		Afterburner		
	Range	Average	Range	Average	
Particulate matter, gr/scf	0.016 to 0.234	0.141	0.011 to 0.070	0.048	66
Aldehydes (as formaldehyde), ppm	8 to 74	40	5 to 61	25	38
Organic acids (as acetic acid)	30 to 156	87	0 to 76	33.5	62
Oxides of nitrogen (as NO_2), ppm	1.2 to 7.2	3.9	3.7 to 33.8	11.7	Negative

Table 222. ANALYSES OF MEAT SMOKEHOUSE EXHAUST GASES BEFORE AND AFTER CONTROL IN TWO-STAGE ELECTRICAL PRECIPITATION SYSTEMS

	Contaminant concentration				Control efficiency, %
	Smokehouse		Control system[a]		
	Range	Average	Range	Average	
Particulate matter, gr/scf	0.33 to 0.181	0.090	0.016 to 0.051	0.032	65
Aldehydes (as formaldehyde), ppm	---	74	---	47	37
Organic acids (as acetic acid), ppm	---	91	---	48	47

[a]Each control system is equipped with a wet centrifugal collector upstream from the precipitator.

Why not immersion?

Conventional smoking operations can be seen as an extremely devious method of coating food products with a myriad of hardwood distillation products. One might wonder why this coating is not applied by simple immersion. Unfortunately, many of the compounds present in smoke are highly toxic. If these were deposited heavily on the food product, results could be fatal. Smoking, therefore, provides a reasonably foolproof, if quaint, means of assuring that these toxic compounds do not accumulate in lethal concentrations. Many states have laws prohibiting the smoking of meats by liquid immersion.

Smoking through electrical precipitation

Some attempts have been made to precipitate smoke particles electrically onto food products in the smokehouse, and a few smokehouses so designed are in operation today. From the operators' point of view, this arrangement offers the advantages of faster smoking and greater use of generated smoke. From the standpoint of air pollution control, it is desirable inasmuch as considerably lesser quantities of air contaminants are vented to the atmosphere than are vented from a conventional, uncontrolled smokehouse.

These units normally consist of a conveyorized enclosure equipped with an ionizer section similar to those used with two-stage precipitators. The food product is usually passed 2 to 3 inches below the ionizing wires, which are charged with about 15,000 volts. No electrical charge is applied to the food products or the conveyor. These smokers are operated at ambient temperatures and do not lend themselves to use for either cooking or drying food products. As would be expected, spacing is a critical factor.

There are very few precipitation smokehouses in the Unites States today, and for this reason, little reliable data about the operating characteristics or the air pollutants emitted are available. Smokehouses of this design have been reported to operate with visible emissions of only 5 to 10 percent opacity. Concentrations of air contaminants in gases from precipitation-type smokehouses would, under optimum conditions, be expected to be approximately equivalent to those from conventional smokehouses equipped with two-stage electrical precipitators.

These units offer the potential of markedly reduced smoking times. Indeed, the few operating units have residence times of less than 5 minutes. If equipment such as this were perfected for a wider range of operation, residence times would not be expected to exceed 10 minutes.

The application of precipitation smokehouses is today limited by a number of inherent problems, the foremost of which is the irregular shape of many smoked products, that is, hams, ham hocks, and salami. The degree of smoke deposition in a unit such as this is governed by the distance between the ionizer and the food product. Irregular spacing results, therefore, in irregular smoking of round and odd-shaped products that cannot be positioned so that all surfaces are equidistant from ionizer wires. The few existing installations are used to impart a light smoke to regular-shaped, flat items such as fish fillets and sliced meat products.

DEEP FAT FRYING

Deep fat or "French" frying involves the cooking of foods in hot oils or greases. Deep-fried products include doughnuts, fritters, croquettes, various potato shapes, and breaded and batter-dipped fish and meat. Most of these foods contain some moisture, a large portion of which is volatilized out as steam during frying. Some cooking oils, as well as animal or vegetable oils from the product, are usually steam distilled during the process.

Batch or Continuous Operation

Deep fat frying is in common usage in homes, restaurants, and frozen food plants. In the home and in smaller commercial establishments, batch-type operation is more common. The principal equipment is an externally heated cooking oil vat. Oil temperatures are usually controlled to between 325° and 400°F. Almost any type of heating is possible. Where combustion fuels are used, burner gases are vented separately. The product to be fried is either manually or mechanically inserted into the hot grease and removed after a definite time interval.

In large commercial establishments, highly mechanized, conveyorized fryers, such as that shown in Figure 550, are used. The raw food product is loaded onto an endless conveyor belt and passed through hot grease at a rate adjusted to provide the proper cook time. Almost all

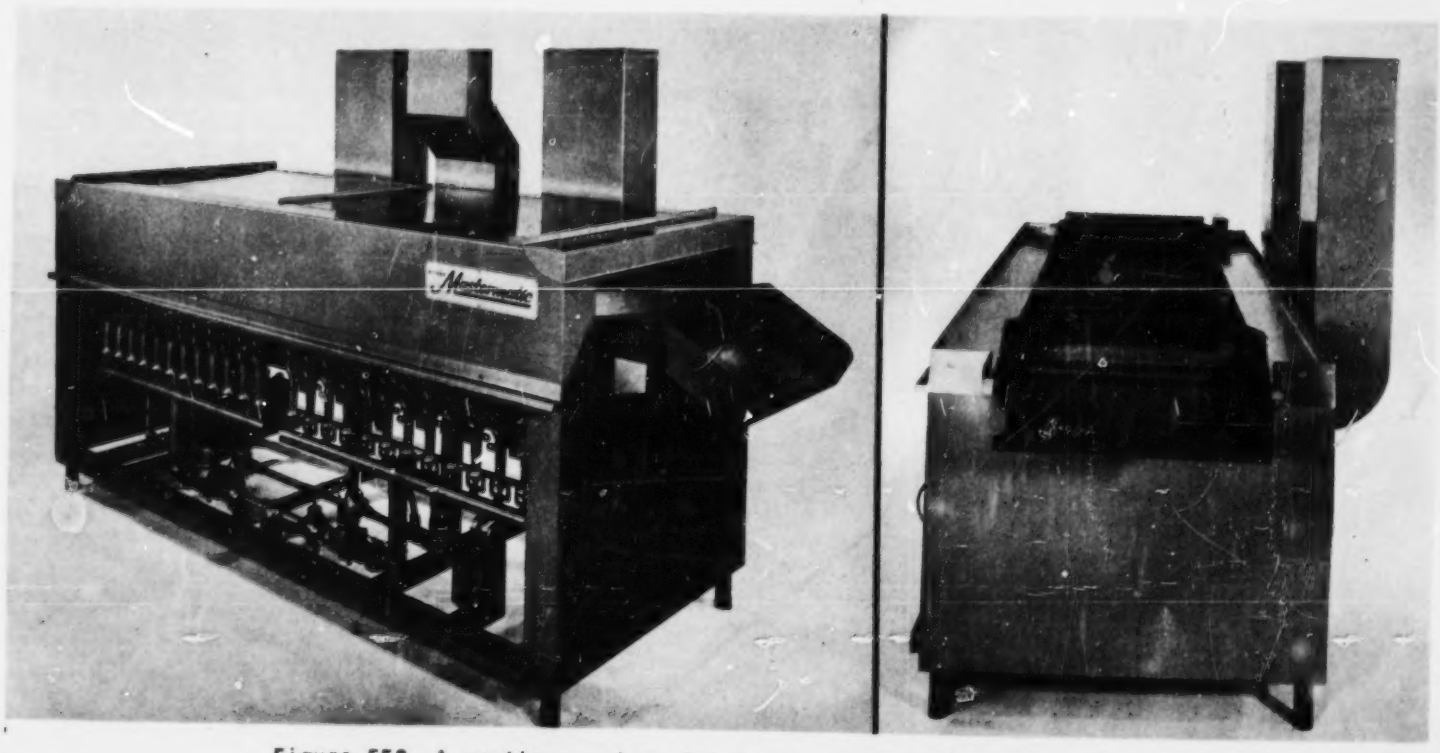


Figure 550. A continuous deep fat fryer: (left) interior view, (right) end view (J.C. Pitman & Sons, Inc., Concord, N.H.).

fryers are of one-pass design. Frequently, cooking units are followed by product coolers and packaging and freezing equipment.

The Air Pollution Problem

In a typical large industrial operation of this type, the cooking vat constitutes the principal source of air contaminants. Uncooked materials are usually wet or pasty, and the feed system produces little or no air pollution. Most cooked-product-handling systems are also innocuous, except in rare instances where fine, dusty materials are encountered.

Odors, visible smoke, and entrained fat particles are emitted from the cooking vats. Depending upon operating conditions and the surrounding area, these contaminants may or may not be in sufficient concentration to exceed the limits of local opacity or nuisance regulations.

From the standpoint of air pollution control, the most objectionable operations involve foods containing appreciable fats and oils. Light ends of these oils are distilled during cooking. In general, the deep frying of vegetable products is less troublesome than that of fish and meat products, which contain higher percentages of fats and oils.

Most food products cooked in this manner contain between 30 and 75 percent moisture before the cooking. Almost all moisture is driven off in the cooking vat and appears as steam in exhaust gases. Moisture concentrations in stack gases are usually between 5 and 20 percent, depending upon the volume of air drawn into the cooker hood and exhaust system. In highly mechanized installations, very little air enters under the cooker hood. As a result, the warm air-stream from a fryer such as this is often saturated, and downstream cooling causes visible condensation at or near the stack exit.

Moisture has two effects: (1) It causes fats and oils to be steam distilled from the cooking vat, and (2) it masks visible stack emissions. Smoke observations of equipment such as this must be made at the point in the stack plume where water vapor has disappeared. This is best accomplished when the weather is warm and dry. On a cold, moist day, the vapor plume may extend as far as the smoke.

Excessive smoking is most often due either to overheating or to the characteristics of the material being cooked. When, for instance, potato chip or corn chip fryers are operated in normal temperature ranges, there is usually no more than a trace of smoke in exhaust gases. On the other hand, several meat product fryers have been found to exhaust gases of high opacity, and control equipment was needed to bring them into compliance with local regulations. These visible emissions appear to be finely divided fat and oil particles distilled either from the product or the cooking oil. Cooking oils are usually compounded within reasonably narrow boiling ranges, and when fresh, very little of the oils is steam distilled. Most objectionable air contaminants probably originate, therefore, in the product or in spent cooking oil.

The carryover of oil droplets can also cause a nuisance by spotting fabrics, painted surfaces, and other property in the surrounding area. This problem is most likely to occur when the raw food contains relatively large concentrations of moisture, a situation in which steam distillation is proportionally higher.

Hooding and Ventilation Requirements

Deep fat fryers should always be hooded and vented through a fan. Axial-flow fans are preferred. Exhaust volumes are governed by the open area under the hood. Where there is open area around the full hood periphery, the indraft velocity should be at least 100 fpm. In many modern units, the dryer sides are completely enclosed, and the only open areas are at the conveyer's inlet and outlet. At these installations, exhaust volumes are considerably lesser, even though indraft velocities are well above 100 fpm. If control equipment is to be employed, exhaust volumes become an important factor. In these instances, redesigning the existing hoods to lower the exhaust rates is often desirable.

Air Pollution Control Equipment

Incineration, low-voltage electrical precipitation, and entrainment separation have been used to control air contaminants from deep fat fryers. Since practically all air contaminants from fryers are combustible, a well-designed afterburner provides adequate control if the operating temperature is sufficiently high. Temperatures from 1,000° to 1,200°F are often sufficient to eliminate smoke-causing particulates and to incinerate odors and eye irritants. The combustion of larger particles usually requires higher temperatures, sometimes as high as 1,600°F. The concentration of particulates in fryer exit gases is, however, normally less than 0.1 grain per scf, which is well below common limits for particulate emissions.

Two-stage, low-voltage electrical precipitators (6,000 to 15,000 volts) can be used to collect a substantial portion of the particulates responsible

for visible air contamination. These devices, unfortunately, do not remove the gaseous contaminants that are usually responsible for odors and eye irritation. As would be expected, the effectiveness of a precipitator depends upon the particular fryer it is serving. If particulates are the only significant contaminants in the exhaust gases, a precipitator can provide an adequate means of control. If, on the other hand, the problem is due to odors of overheated oil or product, a device such as this is of little benefit. For optimum performance, the temperature, humidity, and volume of gases vented to a two-stage precipitator must be controlled within reasonably narrow limits. The oils collected are usually free flowing and readily drain from collector plates. A collection trough should be provided to prevent plate fouling and damage to the roof or other supporting structure on which the precipitator is located.

Oil collection

Entrainment separators have been employed with varying success to remove entrained oils in fryer exhaust stacks. These are most useful where the concentration of oils is relatively large. The material collected can represent a savings in oil and can prevent damage to adjacent roofing. Because of the inherently low collection efficiency of these devices, their use would not be recommended where smoke or odors constitute the major air pollution problem. Some cooking oils usually collect on the inner surfaces of uninsulated exhaust stacks and drain back towards the cooker. Most commercial fryers are equipped with pans to collect this drainage at the bottom of the stack.

LIVESTOCK SLAUGHTERING

Slaughtering operations have traditionally been associated with odorous air contaminants, though much of these odors is due to byproduct operations rather than to slaughtering and meat dressing itself. Slaughtering is considered to include only the killing of the animal and the separation of the carcass into humanly edible meat and inedible byproducts. The smoking of edible meat products, and reduction of edible materials are discussed in this subsection, while the reduction of inedible materials is covered in another part of this chapter.

Cattle-, sheep-, and hog-killing operations are necessarily more extensive than those concerned with poultry, though poultry houses usually handle appreciably larger numbers of animals.

A flow diagram of a typical cattle-slaughtering operation is shown in Figure 551. The animal is stunned, bled, skinned, eviscerated, and trimmed as shown. Blood is drained and collected in a holding tank. After removal, entrails are sliced in a "gut hasher," then washed to separate the partially digested food termed "paunch manure." Many slaughterers have heated reduction facilities in which blood, intestines, bones, and other inedible materials are processed to recover tallow, fertilizer, and animal feeds. The firms that do not operate this equipment usually sell their offal to scavenger plants that deal exclusively in byproducts. Hides are almost always shipped to leather-processing firms. Dressed beef, normally about 56 percent of the live weight, is refrigerated before it is shipped.

The Air Pollution Problem

Odors represent the only air contaminants emitted from slaughtering operations. The odors could be differentiated as (1) those released from the animal upon the killing and cutting, and upon the exposure of blood and flesh to air; and (2) those resulting from the decay of animal matter spilled on exposed surfaces or otherwise exposed to the atmosphere. Odors from the first source are not appreciable when healthy livestock is used. Where nuisance-causing odors are encountered from slaughtering, they are almost always attributable to inadequate sanitary measures. These odors are probably breakdown products of proteins. Amines and sulfur compounds are considered to be the most disagreeably odorous breakdown products.

In addition to these sources, there are odors at slaughterhouse stockyards and from the storage of blood, intestines, hides, and paunch manure before their shipping or further processing.

Air Pollution Control Equipment

As has been explained, odorous air contaminants are emitted from several points in a slaughtering operation. Installing control equipment at each source would be difficult if not impossible. Methods of odor control available include: (1) Rigid sanitation measures to prevent the decomposition of animal matter, and (2) complete enclosure of the operation to capture the effluent and exhaust it through a control device.

Where slaughtering is government inspected, the operators are required to wash their kill rooms constantly, clean manure from stock pens, and dispose of all byproducts as rapidly as possible. These measures normally hold plant odors to a tolerable minimum.

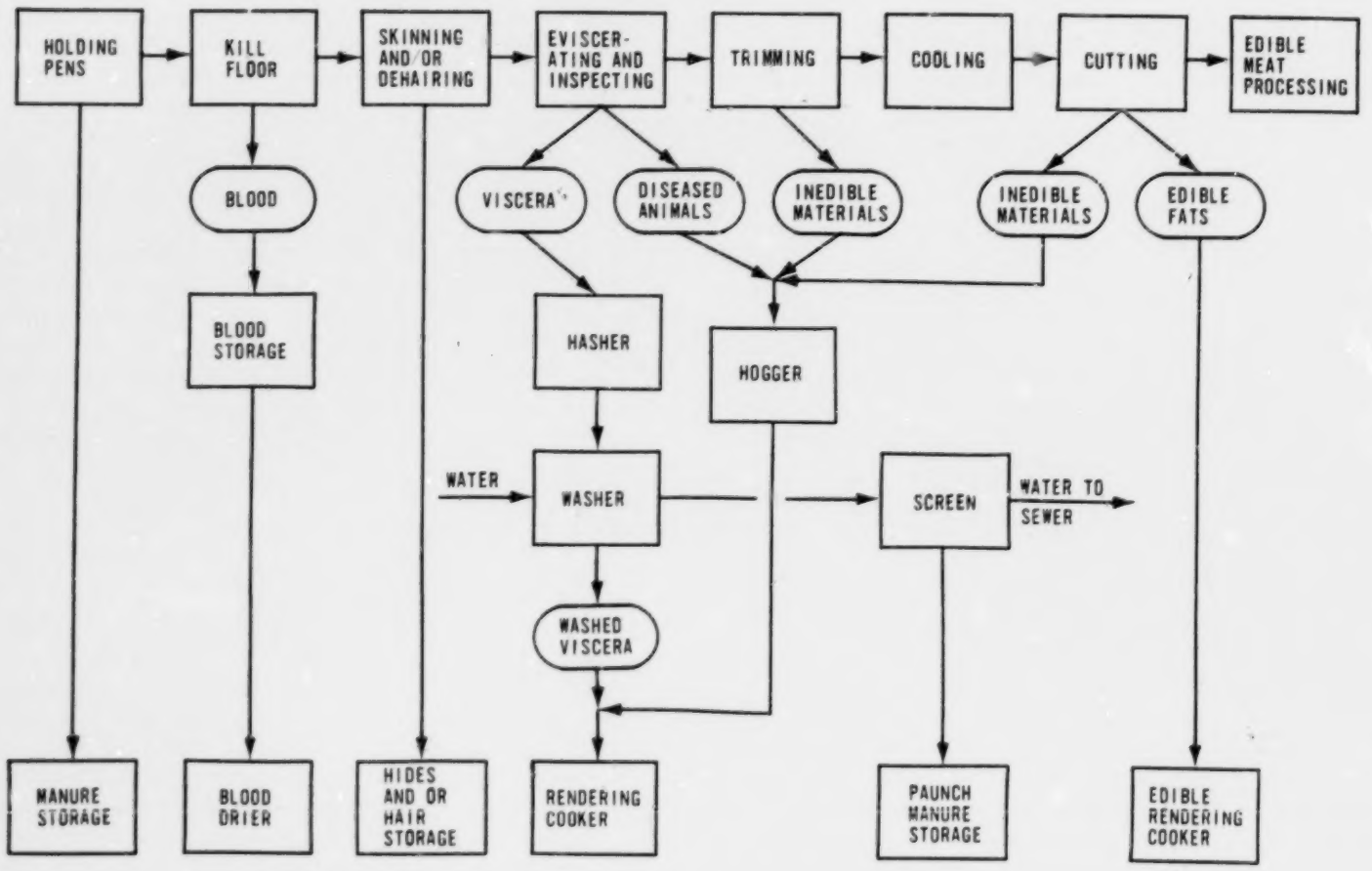


Figure 551. Typical livestock-slaughtering and processing area (The Globe Company, Chicago, Ill.).

When a slaughterer is located in a residential area, the odor reduction afforded by strict sanitation may not be sufficient. In these instances, full-plant air conditioning might be necessary. Filtration with activated carbon would appear to be the only practical means of controlling the large volume of exhaust gases from a plant of this type. The latter method has not yet been employed at slaughterhouses in the United States. Nevertheless, activated-carbon filtration of the entire plant has been employed to control similar odors at animal matter byproduct plants. With increasing urbanization, this method of control may, conceivably, be used in the near future.

EDIBLE-LARD AND TALLOW RENDERING

Methods used to produce edible lard and tallow are similar to those described later in this chapter for rendering of inedibles. As with processes for inedibles, feedstocks are heated either directly or indirectly with steam to effect a phase separation yielding fats, water, and solids. Moisture is removed either by vaporization or by mechanical means. Tallow and solids are mechanically separated from one another in presses, centrifuges, and filters.

The only major process differences between rendering edibles and rendering inedibles are due to the composition and freshness of the materials handled. Edible feedstocks contain 80 to 90 percent lard or tallow, 10 to 20 percent moisture, and less than 5 percent muscle tissue. Inedible feedstocks contain appreciably higher precentages of both moisture and solids. Edible feedstocks, in addition to being more select portions of the animal, are generally much fresher than inedible cooker materials are.

Whenever its products are intended for human consumption, the process is much more stringently supervised and regulated by Federal and local agencies. There are numerous government regulations concerning the freshness of edible-rendering feedstocks, the cleanliness of processing equipment, and the handling of rendered fats. For instance, paragraph 15.1 of the United States Department of Agriculture's Meat Inspection Regulations specifies that inspected feed material must be heated to a temperature not lower than 170°F for a period of not less than 30 minutes when edible lard or tallow is being produced.

Dry Rendering

Most of the high-quality edible lard and tallow are produced in indirectly steam-heated cookers. These processes are frequently carried out at temperatures of less than 212°F. The lower operating temperatures are afforded either by vacuum cooking or by finely grinding the feedstocks. The vacuum process is usually performed batchwise in a horizontal, steam-jacketed cooker very similar to those used for rendering of inedibles. The vacuum is usually created through the use of steam- or water-operated ejectors. Variations in dry, edible-rendering processes are usually concerned with temperatures and the degree of comminution of fats. Where raw materials are ground into fine particles, operation at lower temperatures is usually possible, even without a vacuum-producing device.

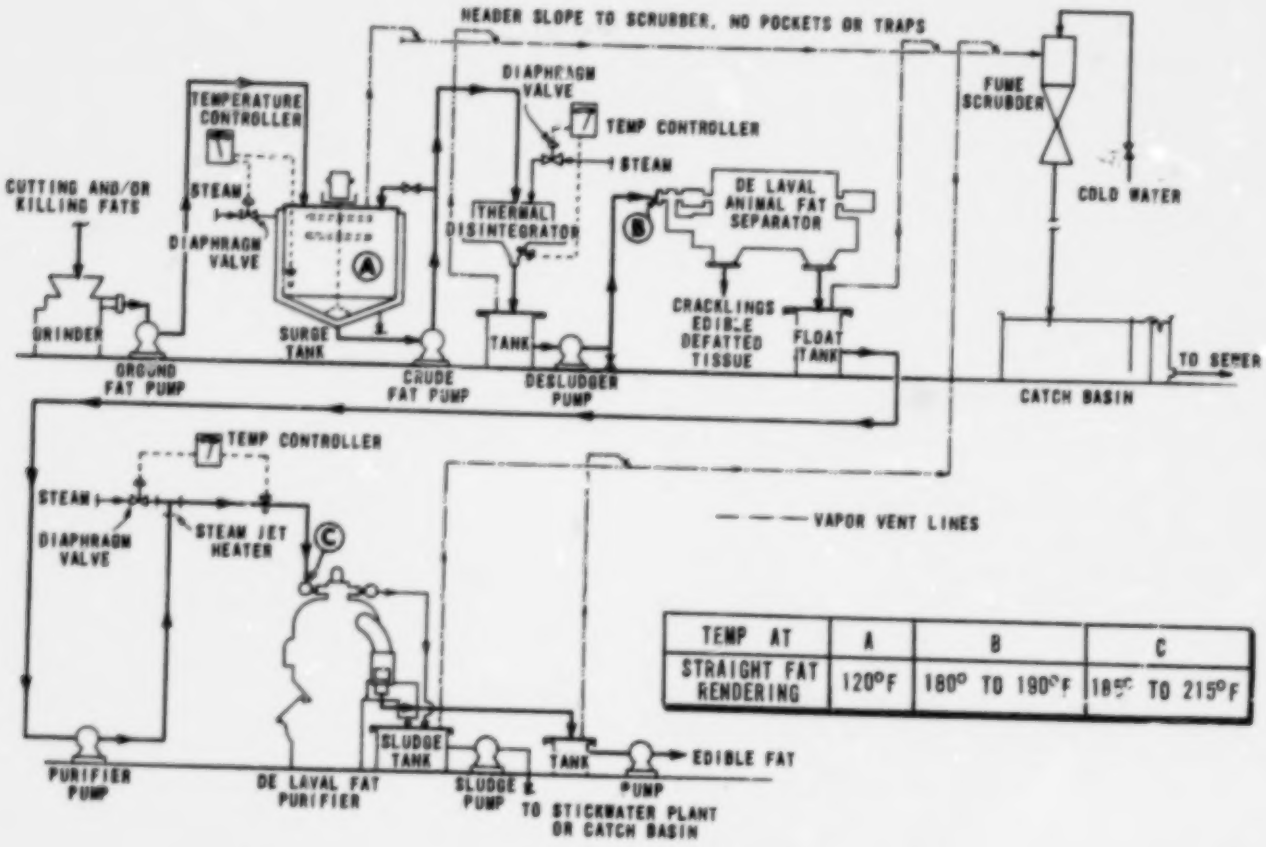
Low-Temperature, Continuous Rendering

Dry rendering processes have been developed to produce edible lard and tallow on a continuous basis from high-fat feedstocks. A typical process is shown in Figure 552. Feedstocks are first introduced to a grinder, where they are finely shredded at 120°F, and then heated to approximately 185°F before being passed through a desludging centrifuge in which solids are removed from the water and tallow. Liquids are then reheated to about 200°F in a steam jet heater. The remaining moisture is removed from the hot tallow in a second centrifuge from which edible lard or tallow is run to storage. The separated water is piped to a skimming pond where it is cooled before being sewered. Vapors from the several vessels are vented to a fume scrubber (contact condenser).

Wet Rendering

The wet rendering process involves rendering of fats in a vertical, closed tank with the feed material in direct contact with live steam.

The principal advantage of this type of rendering is that large quantities of lard or tallow



TEMP AT	A	B	C
STRAIGHT FAT RENDERING	120°F	180° TO 190°F	185° TO 215°F

Figure 552. DeLaval continuous centriflow process for edible protein recovery and edible fat rendering (The DeLaval Separator Co., Millbrae, Calif.).

can be produced without finely grinding the feed material. Low-cost equipment and labor can be used.

Wet rendering, however, necessarily requires higher temperatures (280° to 300°F) and internal pressures of 40 to 38 psig. The quality of the lard or tallow produced is relatively low, owing to the high temperatures to which it is subjected.

The Air Pollution Problem

The only noteworthy air contaminants generated from edible-rendering processes are odors. In comparison with odors generated from inedible-rendering processes, however, those from edible-rendering processes are relatively minor.

In Los Angeles County, rendering of edibles accounts for only about 10 percent of the total animal matter rendered. Rendering of inedibles at packing houses constitutes approximately 32 percent and that at scavenger plants accounts for the remaining 58 percent of the tonnage.

In addition, rates of odor emissions from rendering of edibles are low compared with those from inedible-rendering processes. Inasmuch as edible feedstocks contain relatively low percentages of water, the resultant steam generated from cookers is not appreciable, 6,300 scf per ton. Feedstocks contain approximately 15 percent moisture, as compared with 50 percent from inedible cooker materials. Odor concentrations in exhaust gases from the rendering of edibles are significant at 3,000 odor units per scf but not excessive. Equipment at plants rendering edibles is kept scrupulously clean, which substantially reduces odors from inplant handling operations.

Hooding and Ventilation Requirements

Almost always, cooker gases from rendering of edibles can be piped directly to air pollution control devices. Where condenser odor control devices are used, there is usually enough vacuum, that is, pressure differential, in the ductwork to cause vapors to flow from the cooker at a sufficiently high rate. Steam or water ejectors are sometimes employed to lower operating temperatures or to remove water vapor more rapidly. Uncondensible gases do not exceed 5 percent of cooker gases unless there is appreciable leakage into the system, as through seals on shafts, doors, and so forth.

Where cooking is performed at pressures greater than 1 atmosphere, piping must usually be arranged in a manner that prevents surging when high-pressure gases are released. If the main valve is released quickly, the high-pressure vapors usually cause slugs of grease and solids to be carried over into the control system. Severe surging can cause siphoning of all the material from cooker to the control system. To prevent this, the piping is often arranged with a small pipe, 1 to 2 inches in diameter, that bypasses the main cooker's exhaust line. High pressures are reduced by venting first through the small pipe to the control device. Once the high pressure is relieved, the large valve can be opened to provide greater flow.

Air Pollution Control Equipement

Water spray contact condensers are the simplest devices used for controlling odorous air contaminants from rendering of edibles. These condense a major portion of the steam-laden effluent vapors and dissolve much of the odorous materials. Water requirements of the contact condenser for edible-rendering operations are considerably lower than those for the contact condenser used to control cooker gases from rendering of inedibles. This is due primarily to the lower moisture content of feedstocks and the resultant lower volume of steam exhausted from the cooker. Exit water temperatures should be held below 140°F to prevent the release of volatile, odorous materials from downstream piping and sewers.

Surface condensers are also satisfactory control devices for edible-rendering processes. At the same condensate volume and temperature, however, surface condensers by themselves are not as effective as contact condensers. This is due to the inherently lower condensate volume and larger concentration of odorous materials in the condensate of surface condensers.

That an edible-rendering process would require more extensive odor control than would be afforded by an adequate condenser is unlikely. Nevertheless, uncondensed offgases from condensers could be further controlled by incineration or carbon adsorption, as outlined for processing of inedibles later in this chapter.

FISH CANNERIES AND FISH REDUCTION PLANTS

Canning is the principal method of preserving highly perishable fish foodstuffs. Canneries for this purpose are usually located near harbors where fish can be unloaded directly from boats. Byproduct reduction plants are operated at or near fish canneries to process scrap ma-

terials, and much of the odorous air contaminants generally attributed to canneries emanate from byproduct processes. Only choice portions of sound fish are canned for human consumption. The remainder is converted into byproducts, notably fish oil and high-protein animal feed supplements.

Basically there are two types of fish-canning operations in use today. In the older, so-called "wet-fish" method, trimmed fish are cooked directly in the can. The more popular "precooked" process is used primarily to can tuna. The latter method is characterized by the cooking of whole, eviscerated fish, and the hand sorting of choice parts before canning.

WET-FISH CANNING

Wet-fish canning is used to preserve salmon, anchovies, mackerel, sardines, and similar species that can be obtained locally and brought to the cannery quickly. The distinctive feature of the wet-fish process is the complete removal of heads, tails, and entrails before the cooking. Trimmed and eviscerated raw fish is packed into open cans that are conveyed through a 100- to 200-foot-long hot-exhaust box. Here live steam is employed to cook the fish. Hot-exhaust boxes are vented through several stacks located along their lengths (Figure 553). At the discharge end, cans may be mechanically upended so that "stick water" is decanted from the cans while the cooked fish remains. Stick water consists of condensed steam, juices, and oils that have cooked out of the fish. This liquid is collected and retained for byproduct processing as described later in this section. The cans of drained fish are filled with tomato sauce, olive oil, or other suitable liquid before being sealed. Sealed cans are pressure cooked before their labeling, packing, and shipping.

TUNA CANNING

The precooked canning method was developed to improve the physical appearance of canned fish. It is confined to the commercial canning of larger fishes, principally tuna. Whole, eviscerated fish are placed in wire baskets and charged to live-steam-heated cookers such as those of Figure 554. The cookers are operated

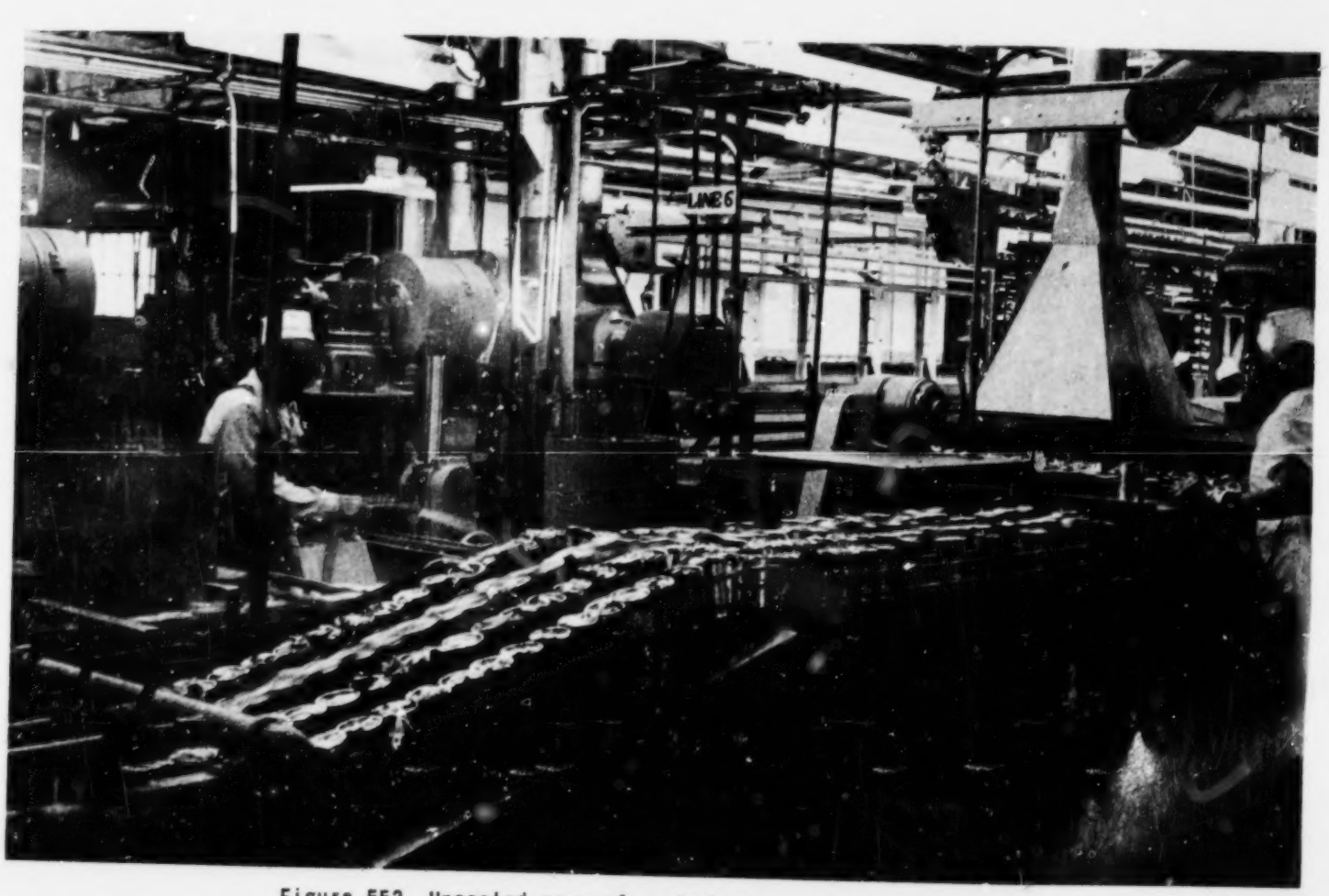


Figure 553. Unsealed cans of cooked mackerel being conveyed from the hot-exhaust box cooker of a wet-fish process (Star-Kist Foods, Inc., Terminal Island, Calif.).

Figure 554. A bank of live-steam-heated cookers used to process raw, whole tuna (Star-Kist Foods Inc., Terminal Island, Calif.).

at about 5 psig pressure, condensate being discharged through steam traps. Air, steam, and any uncondensed, odorous gases are bled from the cookers through one or more small vents in the ceiling.

As the fish are cooked, juices, condensed steam, and oils are collected, centrifuged, and pumped to stick water and oil storage tanks. Cooking reduces the weight of a fish by about one-third. After the cooking, the flesh is cooled so that it becomes firm before it is handled. It is then placed on a conveyorized picking line. Operators stationed along the conveyor select the portions to be canned for human consumption. After being packed and sealed in cans, the fish is pressure cooked for sterilization before its labeling, packing, and shipping. Much of the dark meat is canned for pet food. Only about one-third of the raw tuna weight is canned as food for humans and pets. The remaining skin, bone, and other scrap, roughly amounting to one-third of the raw weight, is fed to the fish meal reduction system.

CANNERY BYPRODUCTS

A large fraction of the fish received in a cannery is processed into byproducts. In the precook process, about two-thirds of the raw fish weight is directed to byproduct reduction systems as stick water or solid scrap. The wet-fish process usually produces somewhat less offal, depending principally upon the size of fish. Typical head-and-tail mackerel scrap is pictured in Figure 555. In addition, whole fish may be rejected at the canning line because of spoilage, freezer burns, bad color, and so forth. Any fish or portions of fish

Figure 555. Typical raw head-and-tail mackerel scrap awaiting processing in a fish meal reduction system (Star-Kist Foods, Inc., Terminal Island, Calif.).

not suitable for human consumption or for pet food are handled in the reduction plant. In order of volume and relative importance, the byproducts are: Fish meal, used almost exclusively as an animal feed supplement; fish oil, used in the paint industry and in vitamin manufacture; and "liquid fish" and "fish solubles," high-protein concentrates. The latter are manufactured somewhat differently, but both are used as animal feed supplements and as fertilizers.

FISH MEAL PRODUCTION

Fish scrap from the canning lines, including any rejected whole fish, is charged to continuous live-steam cookers in the meal plant. Flow through a typical fish meal plant is diagrammed in Figure 556. Cookers of the type shown in Figure 557 are operated at between 2 and 5 psig steam pressure. Material charged to the cookers normally contains 20 30 percent solids. Cooked scrap has a slightly smaller solids content owing to the condensed steam picked up in cooking. After the material leaves the cooker it is pressed to remove oil and water, and this pressing lowers the moisture content of the press cake to approximately 50 percent. The press cake is broken up, usually in a hammer mill, and dried in a direct-fired rotary drier or in a steam-tube rotary drier. Typical fish meal driers yield 2 to 10 tons of meal per hour with a moisture content of 4 to 10 percent. Both types of driers em-

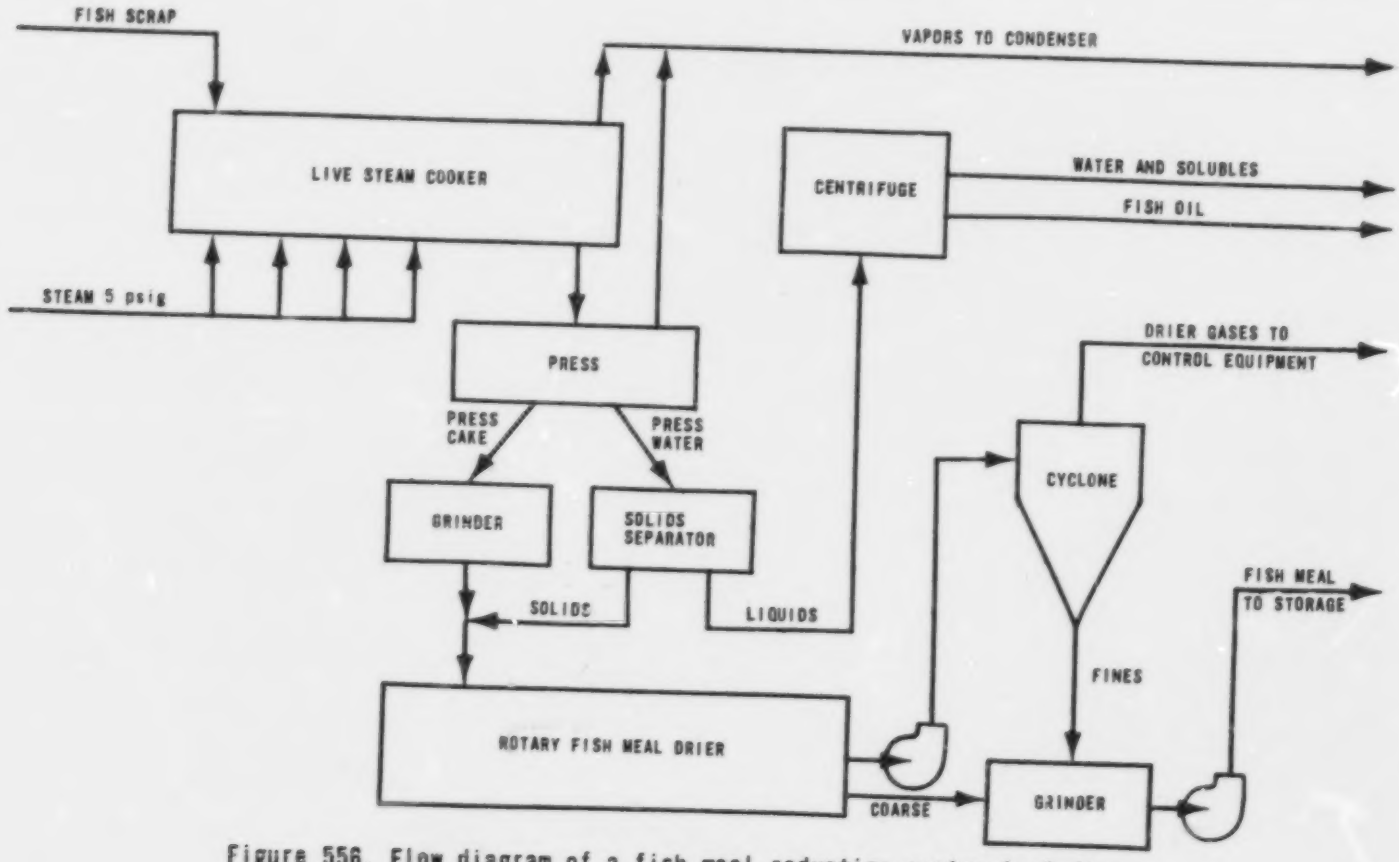


Figure 556. Flow diagram of a fish meal reduction system including oil-separating and oil-clarifying equipment.

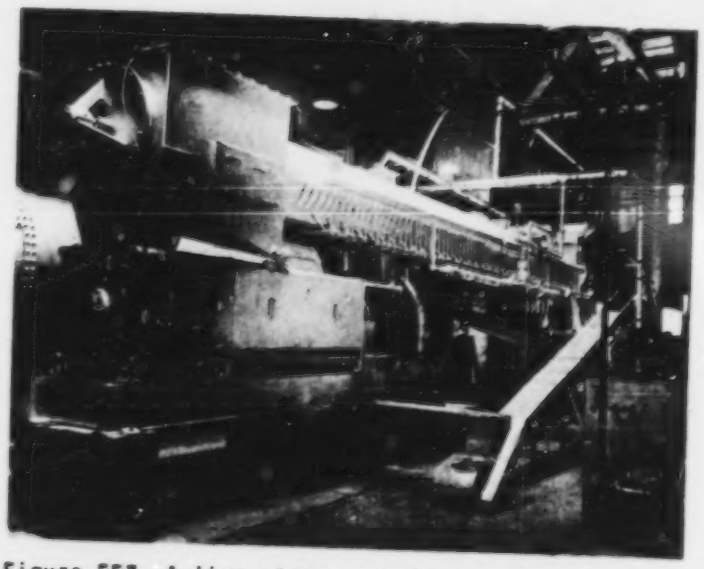


Figure 557. A live-steam reduction cooker and a continuous press (Standard Steel Corp., Los Angeles, Calif.).

ploy air as the drying medium. Moisture is removed with exhaust gases, which are voluminous.

Direct-fired driers include stationary fireboxes ahead of the rotating section, as shown in Figure 558. They are normally fired with natural gas or fuel oil. Combustion is completed in the firebox. Hot products of combustion are mixed with air to provide a temperature of 400° to 1,000°F at the point where wet meal is initially contacted. Hot, moist exhaust gases from the drier contain appreciable fine meal, which is commonly collected in a cyclone separator.

The essential feature of steamtube driers is a bank of longitudinal, rotating steamtubes arranged in a cylindrical pattern, as shown in Figure 559. Steam pressures range from 50 to 100 psig in the tubes. Heat is transferred both to the meal and air. As with direct-fired units, gases pass parallel to meal along the axis of the drier and are vented through a cyclone separator. Meal produced in steamtube driers is less likely to be over-heated and is generally of higher quality than that from direct-fired units.

FISH SOLUBLES AND FISH OIL PRODUCTION

Fish solubles is the term used to designate the molasses-like concentrate containing soluble proteins and vitamins that have been extracted from fish flesh by cooking processes. The flow diagram of Figure 556 includes the separation of press water and fish oil. The sources of solubles and oils are the juices and condensate collected as press water and stick water.

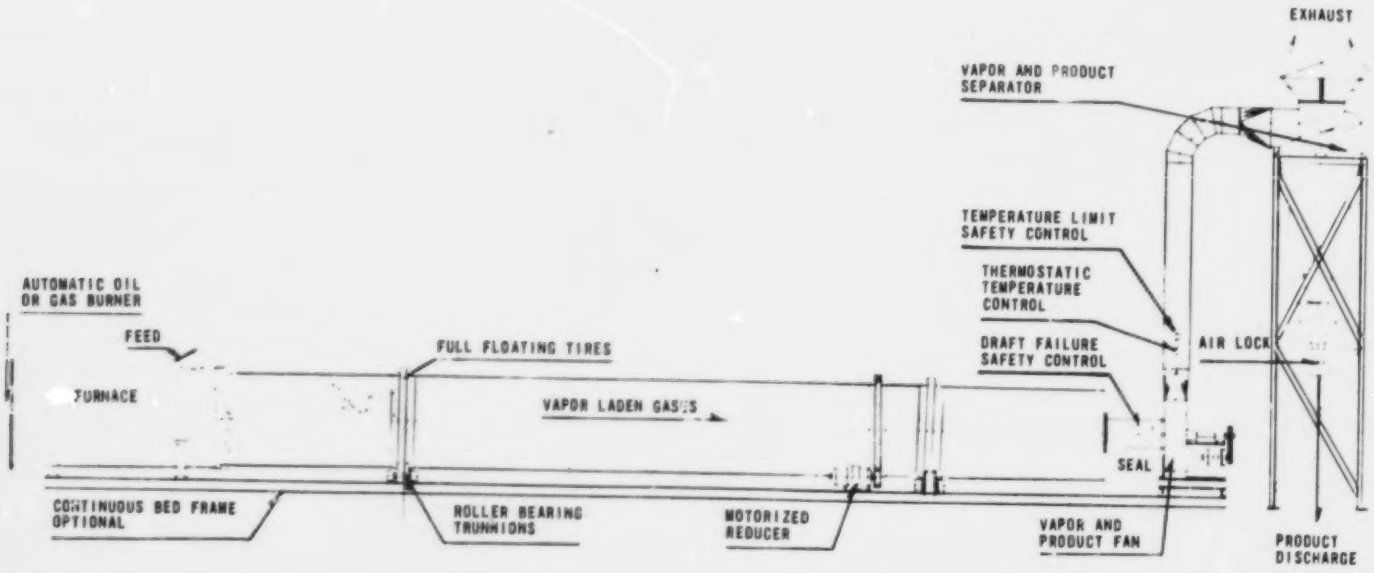


Figure 558. A parallel-flow, direct-fired, rotary, fish meal drier (Standard Steel Corp., Los Angeles, Calif.).

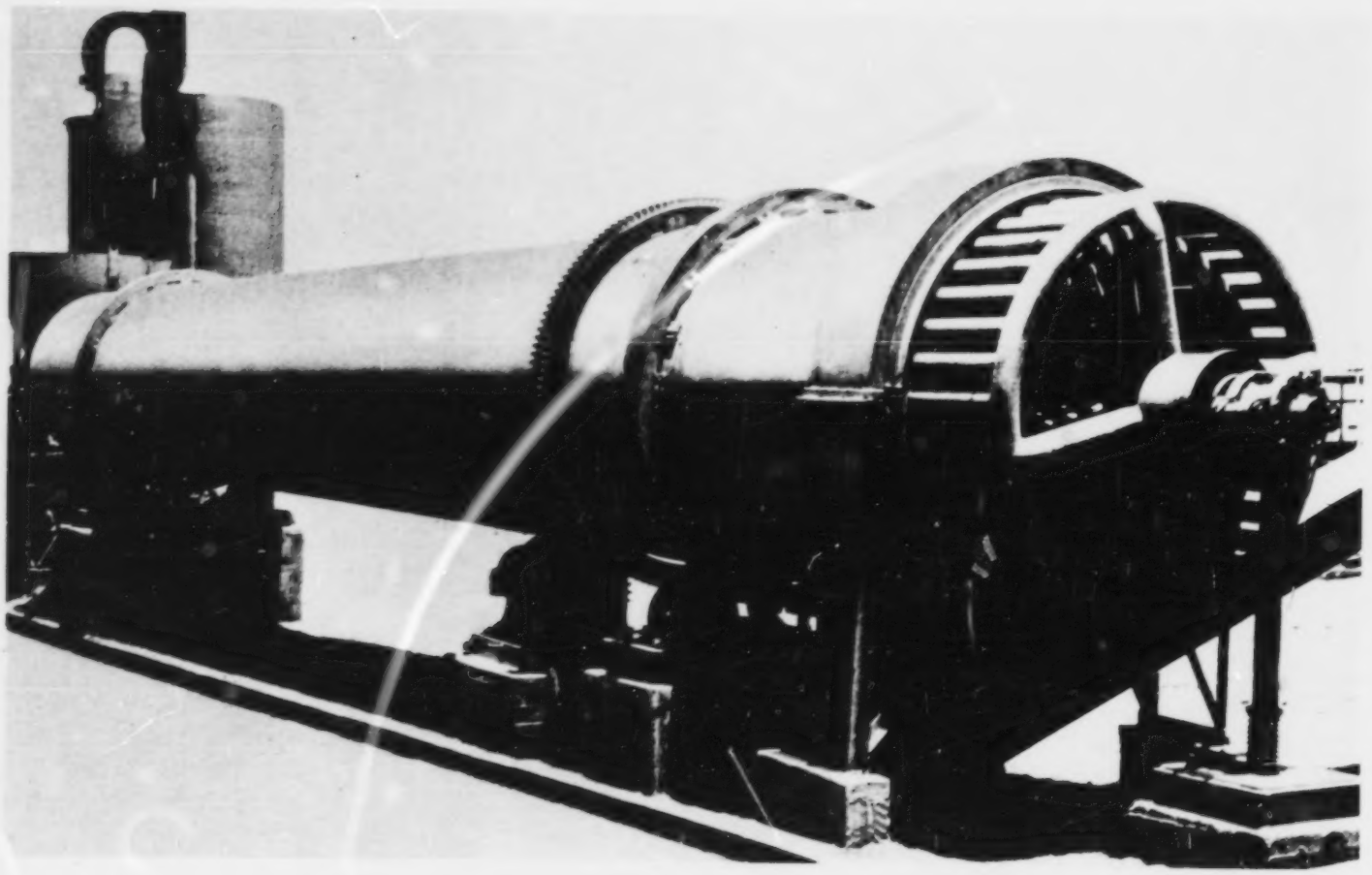


Figure 559. A steamtube, rotary, fish meal drier (Standard Steel Corp., Los Angeles, Calif.).

These two liquids may be processed separately or blended before their processing. The liquids are first acidified to prevent bacterial decomposition. Some protein is flocculated upon the addition of acid. The floc and other suspended solids are removed in a centrifuge and recycled to the fish meal reduction process. Liquids pass through a second centrifuge, where the fish oils are removed. The water layer is pumped to multiple-effect evaporators where the solids content is increased from approximately 6 to 50 percent by weight. Uncondensed gases are removed from the process at one of the evaporator effects, which is operated under high vacuum. The vacuum is held by a water or steam ejector. Where steam ejectors are used they are equipped with barometric-leg aftercondensers.

DIGESTION PROCESSES

Fish viscera are usually digested by enzymatic and bacterial action rather than by thermal reduction. The product is a liquid that is concentrated by evaporation and marketed as a high-protein livestock feed supplement very similar to fish solubles.

Most cannery-operated digestion processes are of the enzymatic type and are used only to process viscera. Stomach enzymes, under controlled pH and temperature, reduce the viscera to a liquid. The process is usually carried out in a simple tank at atmospheric pressure, near-ambient temperature, and an acid pH. Essentially no moisture is evaporated during digestion. Before concentration, the digested liquid is filtered and centrifuged to remove small quantities of scales, bones, and oil. The evaporation process is identical to that used for fish solubles, yielding a liquid of 50 percent solids.

Bacterial digestion is used to reduce all types of fish flesh. It is carried out at an alkaline pH in equipment similar to that used for enzymatic processes. Again, there is no appreciable moisture evaporation, but odors evolved are considerably stronger and more likely to elicit nuisance complaints.

THE AIR POLLUTION PROBLEM

Air contaminants emanate from a number of sources in fish canneries and fish reduction plants, including both edible-rendering and byproduct processes. Odors are the most objectionable of these contaminants, though dust and smoke can be a major problem. In a fish cannery, some odor is unavoidable owing to the nature of the species. Heavy odor emissions that cause nuisance complaints can usually, however, be traced to poor sanitation or inadequate control of air contaminants. Trimethyl amine, $(CH_3)_3N$, is the principal compound identified with fish odors.

Reduction processes produce more odors than cannery operations do. Materials fed to reduction processes are generally in a greater state of decay than the fish are that are processed for human consumption. Edible portions of the fish are always handled first, and great care is maintained to guarantee the quality of edible products. The portions that are unsuitable for human consumption have much less value, and it is not uncommon for operators to allow reduction plant feedstocks to decompose markedly before the processing.

The largest sources of reduction plant odors are fish meal driers. Lesser quantities of odors are emitted from cookers preceding meal driers, from digestion processes, oil-water separators, and evaporators. Dust emissions are limited to driers and the pneumatic conveyors and grinders following them. Smoke can be created by overheating or burning meal in the drier.

Odors From Meal Driers

Fish meal driers exhaust large volumes of gases at significantly large odor concentrations. During the processing of fresh fish scrap, odor concentrations in exhaust gases range from 1,000 to 5,000 odor units per scf (see Appendix for definition of odor units and method of measuring odor concentrations). If the feedstocks are highly decayed, much greater odor concentrations can be expected. The result is an extremely heavy rate of odor emission, even when fresh fish scrap is processed. For example, a direct-fired drier producing 5 tons of dried fish meal per hour exhausts about 44 million odor units per minute if the concentration is 2,000 odor units per scf, and the exhaust rate is 22,000 scfm. Drier exit temperatures average about 200°F, and moisture content normally ranges between 15 and 25 percent by volume.

Emissions from steamtube driers are less voluminous and can be less odorous than those from direct-fired units. With steamtube driers, there is less likelihood of burning or overheating the meal and, therefore, excessively heavy odor concentrations are encountered less often. Moisture contents are comparatively greater in gases from steamtube driers. Typical gases from emitted steamtube driers during tuna scrap processing contain about 25 percent moisture as compared with approximately 15 percent from

a direct-fired unit processing the same material. As a result, volumes from steamtube driers are 30 to 45 percent lower than those from comparable direct-fired units. Odor concentrations from steamtube driers are generally in the same range as those from direct-fired units when fresh fish scrap is being processed under proper operating conditions, that is, when meal is not overheated.

Smoke From Driers

Excessive visible air contaminants can be created in fish meal driers by the overheating of meal and volatilization of low-boiling oils and other organic compounds. Smoke is more likely to be emitted from direct-fired driers than from steamtube units, particularly if flames are allowed to impinge directly on the meal. All driers have limits for gas discharge temperature above which excessive visible contaminants appear in the exit gas stream. For direct-fired units, this limit is about 190°F for tuna scrap and about 215°F for wet-fish scrap. The smoking limit is a function of drier design as well as of feedstocks and varies somewhat from unit to unit.

The addition of certain low-boiling materials to drier feedstocks can also create visible emissions when there is essentially no overheating of meal in the drier. One such material is digested fish concentrate. Some operators add this high-protein liquid to drier feedstocks to upgrade the protein content of meal. Digested fish concentrate can contain low-boiling compounds that are vaporized into exhaust gases and condense upon discharge to the atmosphere. These finely divided, organic, liquid particulates can impart greater than 40 percent opacities to drier gases. Scrubbing the drier gases with water aggravates the problem by lowering the temperature, which increases condensation and, thereby, the opacity.

Dust From Driers and Conveyors

The only major points of dust emission in canneries and reduction plants are the driers themselves and the grinders and conveyors used to handle dried fish meal. Driers and pneumatic conveyors are equipped with cyclone separators, and emissions are functions of collection efficiencies.

Fish meal does not usually contain a large fraction of fines. A particle size analysis of a typical meal is provided in Table 223. This meal sample was collected in a pneumatic conveyor handling ground fish meal. It can be seen that the sample contains only 0.6 percent by weight less than 5 microns in diameter, and 1.4 percent less than 10 microns in diameter. Ninety-six percent is larger than 20 microns.

Table 223. PARTICLE SIZE ANALYSIS OF A TYPICAL GROUND, DRIED FISH MEAL[a]

Range of particle diameter, μ[b]	wt %
0 to 5	0.6
5 to 10	0.8
10 to 20	2.6
20 to 44	7.5
44 to 74	11.5
74 to 149	29.9
149 to 246	16.4
246 to 590	22.8
590 to 1,651	7.4
1,651 to 2,450	0.4
more than 2,450	0.1

[a]Sample drawn from a pneumatic conveyor following a direct-fired drier and hammer mill.
[b]Size determination by micromerograph.

Concentrations of fines in exit gases are usually less than 0.4 grain per scf. The pneumatic conveyor cyclone handling the meal of Table 223 was found to be better than 99.9 percent efficient, with an exit dust concentration of less than 0.01 grain per scf. This efficiency is much greater than would be predicted on the basis of cyclone design and particle size. It indicates that appreciable agglomeration probably takes place in the cyclone.

Odors From Reduction Cookers

The cookers preceding fish meal driers exhaust gases of heavy odor concentration. Nevertheless, the volumes of these offgases are appreciably less than those from driers. Cooker gases are similar to those from indirectly heated rendering cookers. They consist almost entirely of water vapor but contain significant quantities of extremely odorous organic gases and vapors. Odor concentrations from live-steam-heated cookers range from 5,000 to over 100,000 odor units per scf, depending to a large degree upon the state of feedstocks. Any malodorous gases contained in the cellular flesh structure are usually liberated when the material is first heated in the cooker.

Essentially no solids are in the effluent from the cookers, though some entrained oil particulates are usually present. The volumes of exhaust vapors depend upon the degree of sealing provided in the cooker. All the steam can be contained in the cooker with no leakage. Most cookers, how-

ever, are designed to bleed off 100 to 1,000 cfm through one or more stacks. The latter arrangement is recommended, since it provides a positive exhaust point at which air contaminants can be controlled. Otherwise the malodorous gases would be liberated at the press and grinder where they are difficult to contain.

Odors From Digesters

The digestion of fish scrap produces only small volumes of exhaust gases, though these gases can have a large odor concentration. The enzymatic, acid-pH decomposition of viscera does not normally produce odor concentrations greater than 20,000 odor units per scf, depending again upon the quality of feedstocks. Alkaline digestion of fish scrap, on the other hand, is productive of strong odors that are likely to create a public nuisance.

Odors From Evaporators

The evaporation of the water-soluble extracts--stick water and press water--does not generally result in heavy odor emissions. This is primarily due to the use of water ejector-condensers. Odors could be considerably heavier if different types of vacuum-producing equipment were employed. Most fish canneries are located near large bodies of water,and it is common to use water jet ejectors to maintain a vacuum on the evaporator system. All uncondensed gases and vapors from the evaporators are vented to the ejectors, which act as contact condensers. Most of the odorous compounds are condensed or dissolved in the effluent water. If steam ejectors and surface condensers, rather than contact condensers, are used to produce the vacuum, odor emissions to the atmosphere are much greater. Contact condensers (water ejectors) provide a dilution of condensate 10 to 20 times greater than that produced by surface-type condensers used with steam ejectors or vacuum pumps.

Odors From Edibles Cookers

While most odorous air contaminants are considered to emanate from fish reduction processes, the handling and cooking of edible fish also produce measurable odors. The largest single sources are the cookers described earlier in this section.

The precooked process is less productive of odors than the wet-fish process is. When tuna is cooked in the live-steam cookers of Figure 554, much of the odorous gases and vapors is condensed in the cooker and the steam trap. Only the volatile, albeit highly odorous compounds are vented through the steamtrap.

The hot-exhaust boxes of wet-fish production systems are commonly vented directly to the atmosphere. These offgases consist mostly of steam with some noncondensible air and malodorous gases entrained. Hot-exhaust boxes are the points of initial cooking of wet fish, and are, therefore, origins of large quantities of gases and vapors.

HOODING AND VENTILATION REQUIREMENTS

When air pollution control is employed, most fish cannery and reduction processes are vented directly to the control device. The only equipment requiring hooding are the presses and grinders intermediate between cookers and driers in a fish meal system. Hot material from the cooker evolves appreciable steam and odors when the oil and water are pressed from it and when the resultant press cake is broken up before the drying. The vapors liberated at these points consist principally of steam. When the gases are vented to a condenser, hooding should be as tight as possible to prevent dilution with air. Indraft velocities of 100 fpm across the open area under the hood are normally satisfactory. Where possible, the source itself should be totally enclosed and ducted to control equipment. Unfortunately, the designs of many presses and grinders are not conducive to complete enclosure, and hoods must be employed.

The largest contaminated gas streams are exhausted from fish meal driers. As shown in Table 224, volume rates are lower from steamtube driers than from direct-fired units. For the hypothetical comparison made in this table, the fired drier exhausts 70 percent more gases than the steamtube drier does and the moisture content is comparatively lesser, 16.1 against 25 percent. A 10-ton-per-hour fired drier would exhaust 22,830 scfm at about 200°F, while a steamtube unit of the same size would exhaust only 13,500 scfm at about 180°F.

Table 224. CHARACTERISTICS OF EXHAUST GASES FROM TYPICAL DIRECT-FIRED AND STEAMTUBE FISH MEAL DRIERS[a]

	Steamtube drier	Direct-fired drier
Moisture evaporated from meal, scfm[b]	338	338
Natural gas fuel, scfm[c]	-	14
Moisture in products of combustion, scfm	-	31
Total moisture in exhaust gases, scfm	338	369
Dry exhaust gases, scfm	1,012	1,914
Total exhaust gases, scfm	1,350	2,283
Moisture content, % by volume	25	16.1
Temperature of exhaust gases, °F	180	205

[a]Basis: 1 ton of feed per hour to drier. Moisture content of press cake to drier, 50% by weight.
[b]Moisture content of dried meal, 4% by weight.
[c]Natural gas of 1,100 Btu per scf gross heating value.

Exhaust volumes from live-steam-heated cookers range from 100 to 1,000 cfm and depend to a large degree upon cooker design. Inlet and exit seals should be tight to prevent leakage. Most cookers are vented through a single stack.

Digestion tanks with a capacity of 2,000 gallons or less seldom exhaust more than 50 scfm. Exhaust volumes from digesters vary appreciably during the processing of a batch, exit rates being negligible much of the time.

Where water ejector contact condensers are employed on evaporators, exhaust rates are well below 50 scfm. If surface condensers or vacuum pumps are employed instead of contact condensers, exhaust volumes can exceed 100 cfm.

Fish meal pneumatic conveyors are designed to provide from 45 to 70 cubic feet of air per pound of meal conveyed. A pneumatic conveyor handling 5 tons of dried meal per hour exhausts about 10,000 cfm.

Exhaust gases from cookers used in the precooked tuna process are relatively small in volume and include only those gases that are not condensed or dissolved at the steamtrap or the cooker itself. Gases evolved from the hot-exhaust boxes of the wet-fish lines are considerably more voluminous.

AIR POLLUTION CONTROL EQUIPMENT

Fish cannery and fish reduction equipment are controlled principally with condensers, scrubbers, afterburners, and centrifugal dust collectors. Where odors are concerned, incineration is preferable if it can be adapted to the process. Incineration provides the most positive control of nuisance-causing odorous compounds. Condensers are effective where exhaust gases contain appreciable moisture, while centrifugal collectors are usually satisfactory to prevent excessive dust emissions. Scrubber-chlorinators find particular use in the control of odors from fish meal driers.

Controlling Fish Meal Driers

Because of the exceedingly large volume of malodorous exhaust products from driers, they constitute the most costly air pollution control problem in a reduction plant. Drier gases normally contain only 15 to 25 percent moisture. Thus, even after condensation, the volume is great. Moreover, there are enough entrained solids in drier exit gases to make incineration difficult.

Incinerating Drier Gases

Incineration of odorous air contaminants from fish meal driers is possible, though costly. A properly designed afterburner control system requires a dust collector ahead of the afterburner to remove solids that cannot readily be burned. The incineration of solid particulates at 1,200°F or lower can result in partial oxidation of particulates, which tends to increase rather than decrease odor concentrations. A contact condenser-scrubber removes much of the difficult-to-burn particulates and materially reduces the volume rate by condensing the moisture. If the particulate matter concentration in gases to the afterburner is sufficiently small, incineration at 1,200°F reduces odor concentrations to about 50 odor units per scf. Owing to the high cost of fuel in such an arrangement, few large installations of afterburners serve fish meal driers. To make incineration economically attractive, heat from the afterburner should be reclaimed in some manner. The most likely arrangement is the preheating of air to the drier. An afterburner operating at 1,200°F provides all the heat necessary to operate the drier, which thus eliminates the need for a firebox.

Chlorinating and Scrubbing Drier Gases

A unique scrubber-chlorinator design has been developed to control satisfactorily the odors from fish meal driers. This unit is demonstrated in the flow diagram of Figure 560 and pictured in Figure 561. The process depends largely upon the reaction of chlorine gas with odorous compounds at drier exit temperatures. As shown in Figure 560, gases from the drier are first directed through a cyclone separator to remove fine particulates. Chlorine is then added at a rate calculated to provide a concentration of 20 ppm by volume in the gas stream. The reaction is allowed to proceed at about 200°F--the drier exit temperature--in the ductwork for approximately 0.6 second before being chilled and scrubbed with sea water in a packed tower. Gases pass up through the packing countercurrently to the sea water.

In Figure 562, odor concentrations from the scrubber exit are plotted against the chlorine addition rate at constant gas and sea water throughput. As can be seen from the curve, odors reach a minimum at about 20 ppm chlorine. When more than 20 ppm are added, chlorine odors become readily detectable in treated gases, and odor concentrations tend to increase. All the odor measurements used to draw this curve were made on drier gas samples taken between 170° and 205°F, when there was essentially no overheating of meal in the drier.

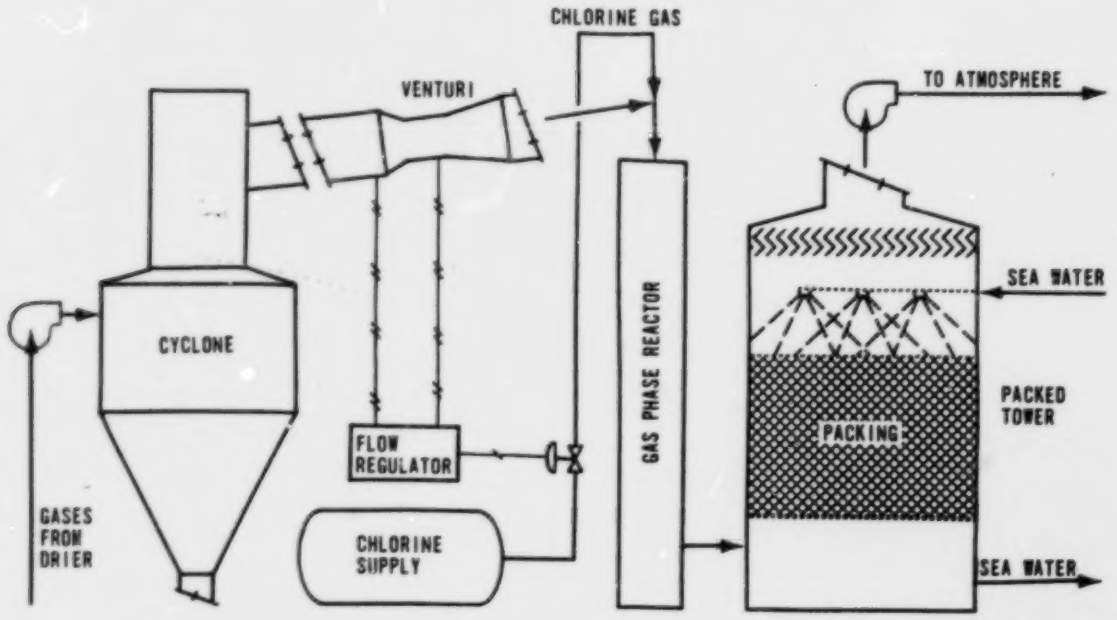


Figure 560. A chlorinator-scrubber odor control system venting a fish meal drier.

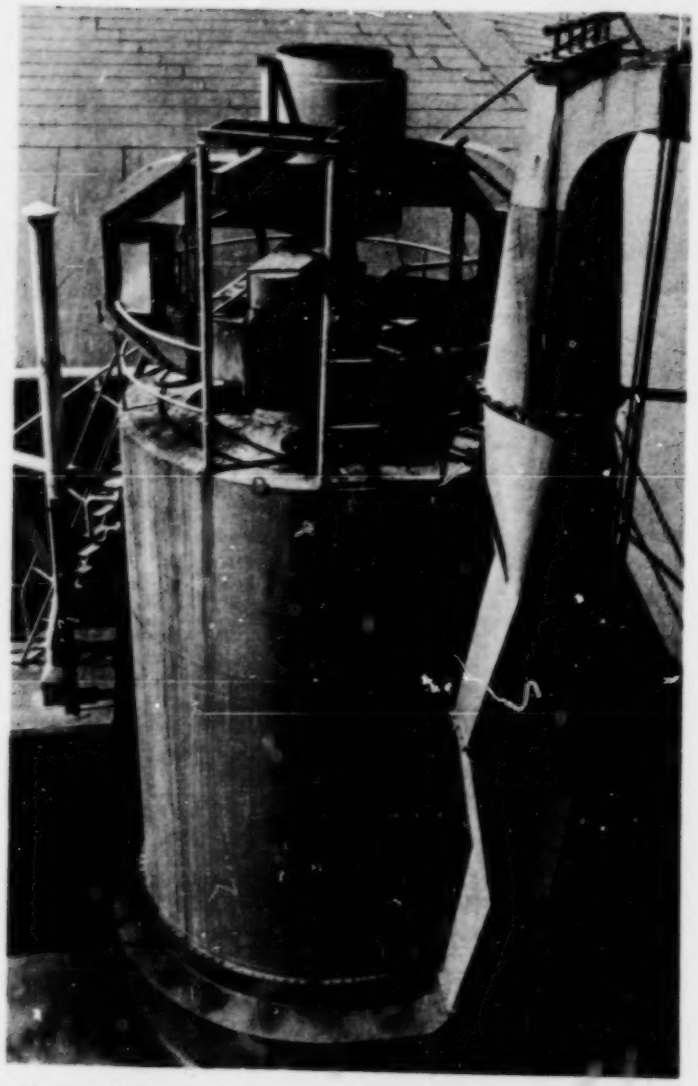


Figure 561. A chlorinator-scrubber odor control system venting a fish meal drier (Star-Kist Foods, Inc., Terminal Island, Calif.).

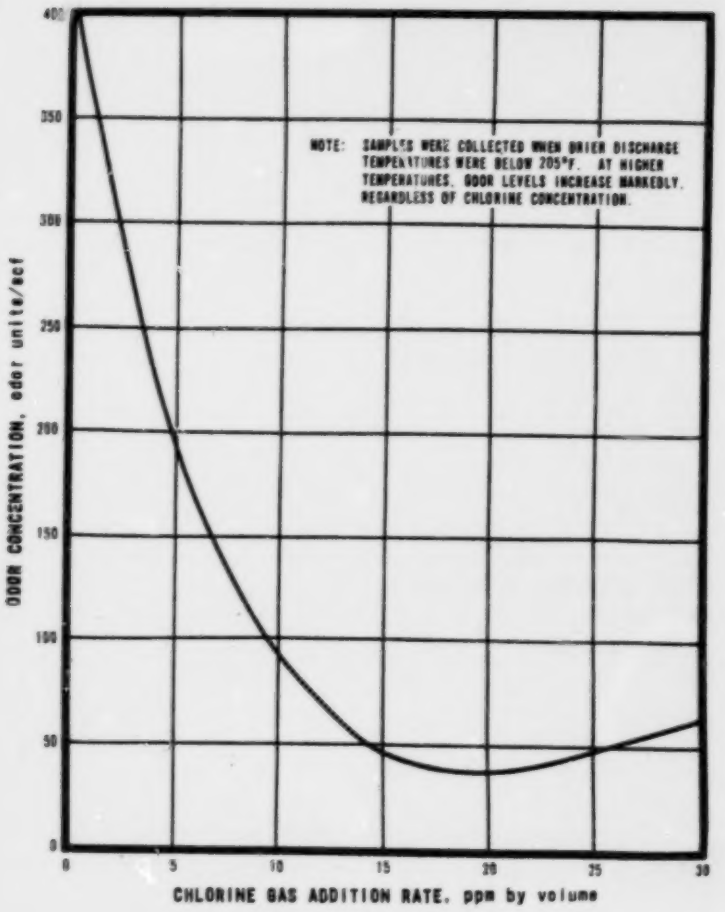


Figure 562. Exit odor concentrations from a chlorinator-scrubber as a function of the chlorine gas addition rate. Temperatures of gas discharged from drier are less than 205°F.

This method provides an overall odor reduction of 95 to 99 percent when fresh fish scrap is being processed in the drier. Chlorination itself provides a 50 to 80 percent reduction in odor concentration. Scrubbing reduces the remaining odor concentration by another 50 to 80 percent. Condensation provides a 12 to 22 percent reduction in volume, depending upon the original moisture content of the gases.

The exact mechanism of the chlorination reaction is uncertain, but it is assumed that chlorine reacts with odorous compounds, probably amines, to form additional products that are less odorous than the original compounds. Chlorine is not considered to be a sufficiently strong oxidizing agent to oxidize fully the odorous organic materials present in drier gases.

Controlling Reduction Cookers

Inasmuch as cooker emissions consist primarily of steam, they can be controlled with condensers and secondary controls if necessary. A contact condenser operating at 100°F or a lower effluent temperature can remove a major portion of cooker odors. If noncondensable gases from the condenser are large in volume, they can be directed to an afterburner, a carbon adsorber, or a chlorinator-scrubber. Normally, there is little entrained air or other noncondensable gases in cooker vapors.

Controlling Digesters

Digester gases are most easily controlled with afterburners. These gases are small in volume and require only minimal fuel for incineration. Digester offgases contain no appreciable moisture or particulates. Odor concentrations can normally be reduced by 99 percent or more at 1,200°F in a properly designed afterburner.

Controlling Evaporators

Evaporators for stick water, press water, and digested liquor can be controlled with condensers and afterburners and combinations thereof. Most evaporators are equipped with water ejector contact condensers to provide the necessary vacuum in the one effect of the multiple evaporator effects. Condensate temperatures from these ejectors are usually less than 80°F. As a result, they condense and dissolve most of the odorous compounds that would otherwise be discharged to the atmosphere. Condensate cannot be circulated through cooling towers without causing the emission of strong odors. Ideally, sea water or harbor water is used for this purpose, with no recirculation. The entrained air contaminants do not add enough material to tail waters to create a water pollution problem.

If water ejectors are not used, odorous air contaminants are emitted in much heavier concentration. The most likely alternative is a steam ejector and surface-type aftercondenser, possibly with multiple ejector stages. Noxious odors from an operation such as this are stronger and more voluminous than those emitted from contact condensers. An afterburner operating at 1,200°F or greater is usually the most practical means of controlling these processes. Activated carbon can be used in lieu of an afterburner.

Collecting Dust

As previously noted, fish meal does not contain a large amount of extremely fine particles, that is, those less than 10 microns. For this reason, cyclone separators are normally sufficient to prevent excessive emissions from the drier and subsequent pneumatic conveyors. If the meal from a particular plant were to contain appreciably more fine material than the sample shown in Table 223, more efficient dust collectors, such as small-diameter, multiple cyclones or baghouses, would have to be used.

Controlling Edible-Fish Cookers

Exhaust gases from both precooked and wet-fish process cookers consist essentially of water vapor. At tuna cookers, most of this vapor is condensed in the steamtraps on the cookers. If further control is desired, an afterburner, carbon adsorber, or low-temperature contact condenser is recommended.

The hot-exhaust boxes of wet-fish processes represent large odor sources that can be controlled with contact condensers, often at little expense to the operator. Most canneries are located near large bodies of water. Sea water or harbor water can be directed to contact condensers at little cost in these instances. Since exhaust box gases are principally water, there is a marked reduction in volume across a condenser such as this, in addition to a decrease in odor concentration.

REDUCTION OF INEDIBLE ANIMAL MATTER

Animal matter not suitable as food for humans or pets is converted into salable byproducts through various reduction processes. Animal matter reduction is the principal waste disposal outlet for slaughterhouses, butcher shops, poultry dressers, and other processors of

flesh foods. In addition, it is used to dispose of whole animals such as cows, horses, sheep, poultry, dogs, and cats that have died through natural or accidental causes. If it were not for reduction facilities, these remains would have to be buried to prevent a serious health hazard. The principal products of reduction processes are proteinaceous meals, which find primary use as poultry and livestock feeds, and tallow.

Much reduction equipment is operated in meat-packing plants to handle only the "captive" blood, meat, and bone scrap offal produced on the premises. Other reduction cookers and driers are located in scavenger rendering plants, which are operated solely for the byproducts. In Figure 563, "dead stock" is shown awaiting dismemberment at a scavenger plant. Common rendering cooker feedstocks are pictured in Figure 564. In general, the materials processed in captive packing house systems are fresher than those handled at scavenger plants where feedstocks can be highly decayed. Typical slaughterhouse yields of inedible offal, bone, and blood are listed in Table 225.

The animal matter reduction industry has been traditionally considered one of the "offensive trades."[1] The reputation is not undeserved. Raw materials and process exhaust gases are highly malodorous and capable of eliciting nuisance complaints in surrounding areas. In recognition of these facts, specific air pollution control regulations have been enacted requiring the control of odorous process vapors.

Figure 563. Dead stock awaiting skinning and dismemberment at a scavenger rendering plant (California Rendering Co., Ltd., Los Angeles, Calif.).

Figure 564. Inedible animal matter in the receiving pit of a rendering system (California Rendering Co., Ltd., Los Angeles, Calif.).

Table 225. INEDIBLE, REDUCTION PROCESS RAW MATERIALS ORIGINATING FROM SLAUGHTERHOUSES
(The Globe Co., Chicago, Ill.)

Source, lb live wt	Inedible offal and bone, lb/head	Blood, lb/head
Steers, 1,000	90 to 100	55
Cows	110 to 125	--
Calves, 200	15 to 20	5
Sheep, 80	8 to 10	4
Hogs, 200	10 to 15	7

Rendering, itself, is a specific, heated reduction process wherein fat-containing materials are reduced to tallow and proteinaceous meal. Blood drying, feather cooking, and grease reclaiming are other reduction operations usually performed as companion processes in rendering plants.

Reduction processes are influenced largely by the makeup of feedstocks. As can be seen from Table 226, some materials, such as blood and feathers, are essentially grease free, while others contain more than 30 percent tallow.

Table 226. COMPOSITION OF TYPICAL INEDIBLE RAW MATERIALS CHARGED TO REDUCTION PROCESSES
(The Globe Co., Chicago, Ill.)

Source	Tallow or grease, wt %	Solids, wt %	Moisture, wt %
Packing house offal and bone			
Steers	15 to 20	30 to 35	45 to 55
Cows	10 to 20	20 to 30	50 to 70
Calves	8 to 12	20 to 25	60 to 70
Sheep	25 to 35	20 to 25	45 to 55
Hogs	15 to 20	18 to 25	55 to 67
Dead stock (whole animals)			
Cattle	12	25	63
Cows	8 to 10	23	67 to 69
Sheep	22	25	53
Hogs	30	25 to 30	40 to 45
Blood	-	12 to 13	87 to 88
Feathers (from poultry houses)	-	20 to 30	70 to 80
Butcher shop scrap	37	25	38

Where no tallow is present, the reduction process becomes primarily evaporation with, possibly, some thermal digestion.

DRY RENDERING

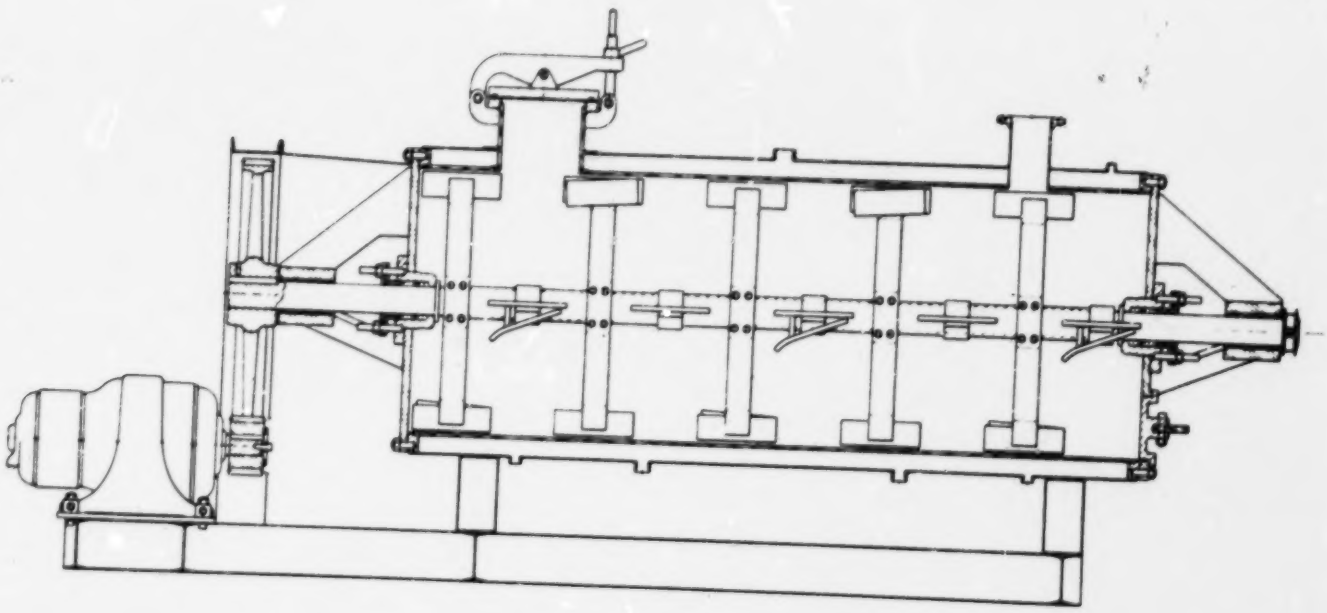
The most widely used reduction process is dry rendering, wherein materials containing tallow are heated indirectly, usually in a steam-jacketed vessel. Heat breaks down the flesh and bone structure, allowing tallow to separate from solids and water. In the process, most of the moisture is evaporated. Emissions consist essentially of steam with small quantities of entrained tallow, solids, and gases.

Dry rendering may be performed batchwise or continuously and may be accomplished at pressures greater or less than atmospheric. A typical batch-type, steam-jacketed, dry rendering cooker is shown in Figure 565. These vessels are normally charged with 3,000 to 10,000 pounds of animal matter per batch. The cookers are equipped with longitudinal agitators that are driven at 25 to 65 rpm. Each batch is cooked for 3/4 to 4 hours.

Pressures of 50 psig and greater are used to digest bones, hooves, hides, and hair. At the resulting temperature (about 300°F), these materials are reduced to a pulpy mass. In typical dry-pressure-rendering cycles, the cooker vent is initially closed to cause pressure and temperature to increase. Some materials are cooked as long as 2 hours at elevated pressure to obtain the necessary digestion. After pressures are reduced, the batch is cooked or dried to remove additional moisture and to complete tallow-solids separation.

Some dry rendering operations are carried out under vacuum to remove moisture rapidly at temperatures sufficiently low to inhibit degradation of products. Vacuum rendering processes are essentially all of the batch type. The vacuum is usually produced with a precondenser, steam ejector, and aftercondenser. Cooker pressures are close to atmospheric at the start, then diminish markedly as the moisture content of the charge decreases. Vacuum rendering produces high-quality tallow but has a disadvantage in that temperatures are low and incomplete cooking of bones, hair, and so forth, may occur.

Highly mechanized, continuous, dry rendering processes are in use in some parts of the United States. Many processes consist essentially of a series of grinders, steam-jacketed conveyor-cookers, and presses. Animal matter is ground before it is fed to a precooker. After the initial cook, the material is again ground before its final processing in the second-stage cooker. Tallow and steam vapors are removed from solids at various points in the system. Cooked material from the second stage is pressed to remove residual tallow. The continuous system of Figure 566 is unique in that it uses recycled tallow, and a vertical-tube vacuum cooker. Selected meat and bone scrap is ground and slurried with hot tallow before being charged to the cooker. Slurry is circulated through the tubes, and vapors are vented to a contact condenser. Steam is condensed ahead of the ejec-



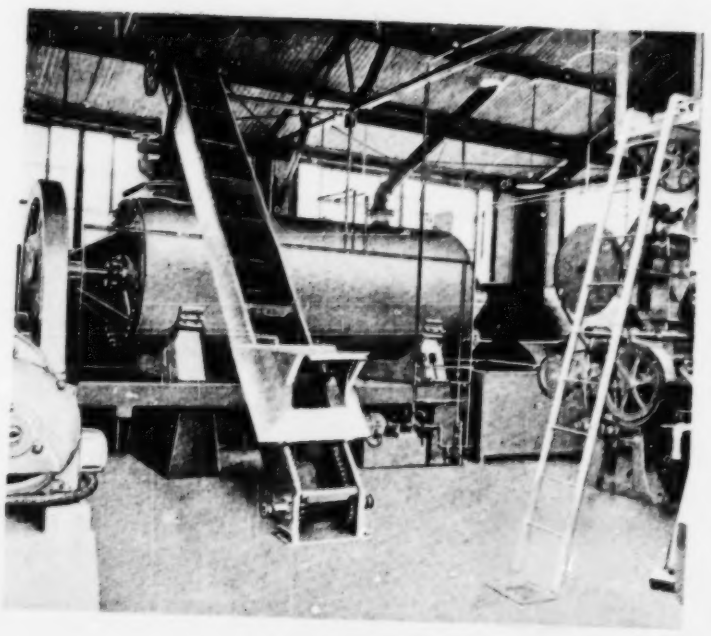


Figure 565. A horizontal, batch-type, dry-rendering cooker equipped with a charging elevator (Standard Steel Corp., Los Angeles, Calif.).

tor, and a barometric leg is employed. Tallow and solids are continuously drawn from the bottom of the cooker.

WET RENDERING

One of the oldest reduction methods is the wet process, wherein animal matter is cooked in a closed vessel with live steam. There is little evolution of steam. Most of the contained moisture is removed as a liquid. Live steam is fed to a charge in a closed, vertical kettle until the internal pressure reaches approximately 60 psig (about 307°F). Heat causes a phase separation of water, tallow, and solids. After initial cooking, the pressure is released, and some steam is flashed from the system. The charge is then cooked at atmospheric pressure until tallow separation is complete. Water, tallow, and solids are separated by settling, pressing, and centrifuging.

The water layer from a wet rendering process contains 6 to 7 percent solids. Soluble proteins can be recovered by evaporation, as in the processing of stick water at fish reduction plants.

Wet rendering finds some use today in the handling of dead stock, namely whole animals that have died through accidents or natural causes. It has given way to dry rendering at most packing houses and scavenger plants. Wet rendering is used to a limited degree in the production of edible fats and oils, as noted previously in this chapter.

REFINING RENDERED PRODUCTS

At the completion of the cook cycle, tallow and solids are run through a series of separation equipment as in the integrated plant of Figure 567. Some systems are more complex than others, but the essential purpose is to produce dry, proteinaceous cracklings and clear, moisture-free tallow. In almost all cases, the cookers are discharged into perforated percolator

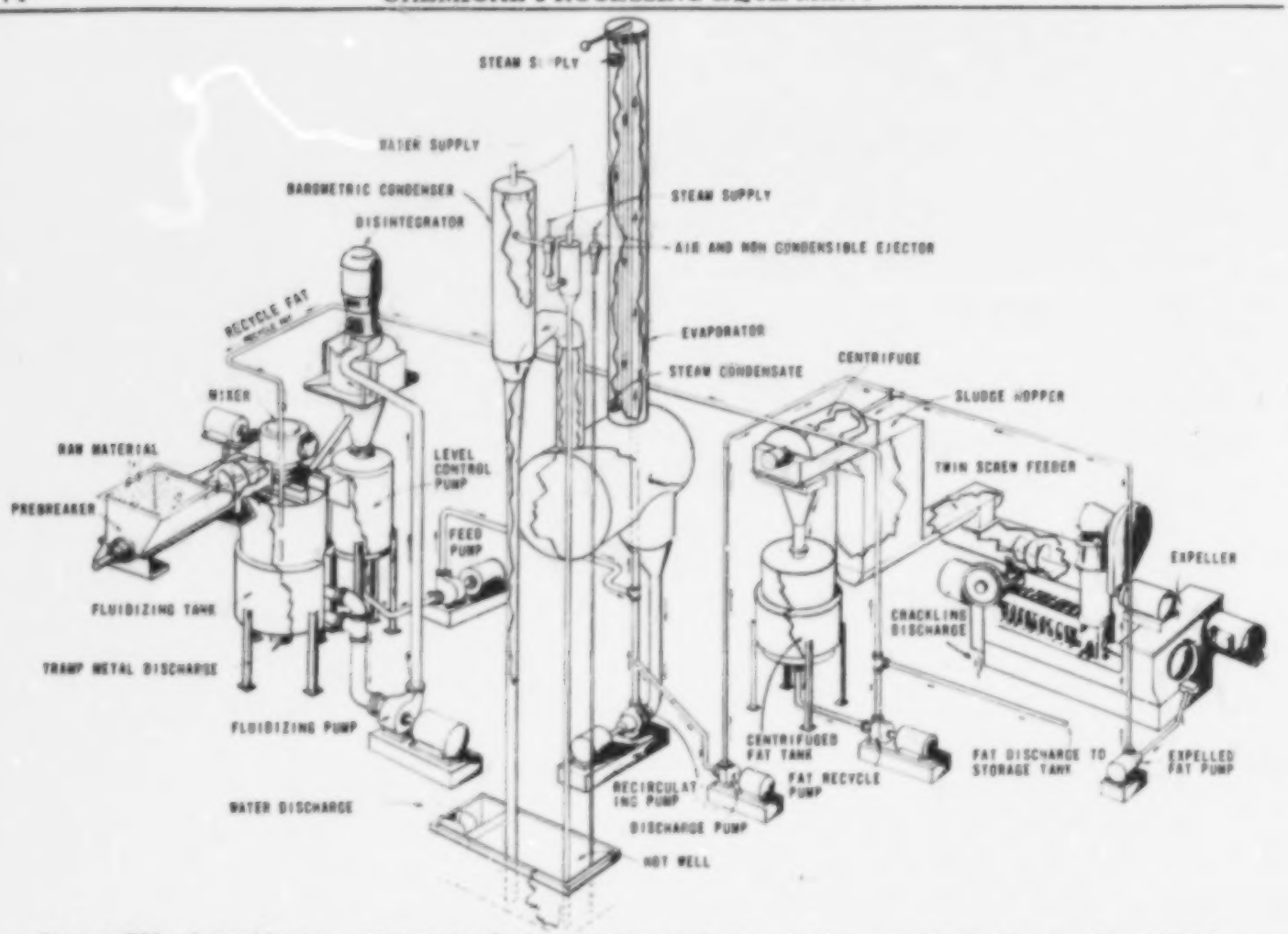


Figure 566. A continuous, vacuum rendering system employing tallow recycling (Carver-Greenfield Process, The V.D. Anderson Co., Cleveland, Ohio).

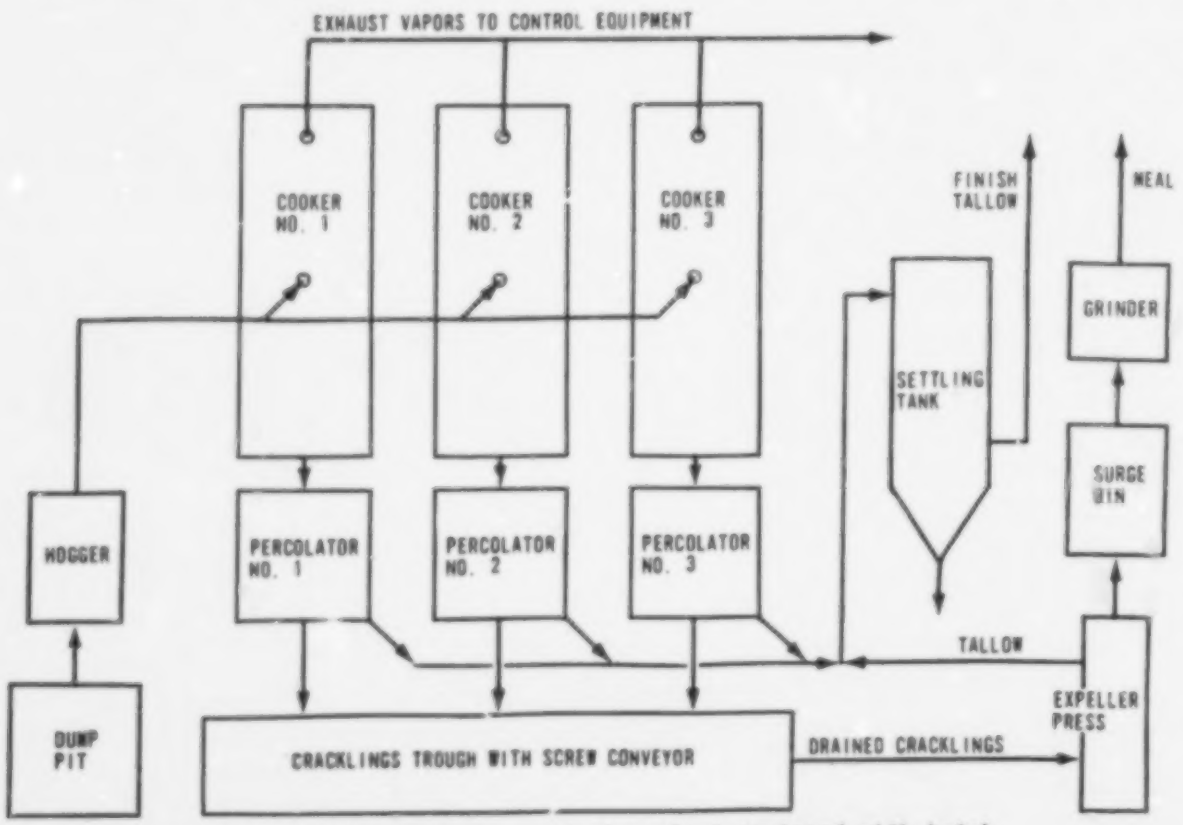


Figure 567. An integrated dry rendering plant equipped with batch cookers, percolators, a cracklings press, and a tallow-settling tank.

pans that allow free-running tallow to drain from hot solids. The remaining solids are pressed to remove residual tallow. Dry cracklings are usually ground to a meal before being marketed. In Figure 568, grease-laden cracklings are being dumped from a percolator pan after free tallow has been drained.

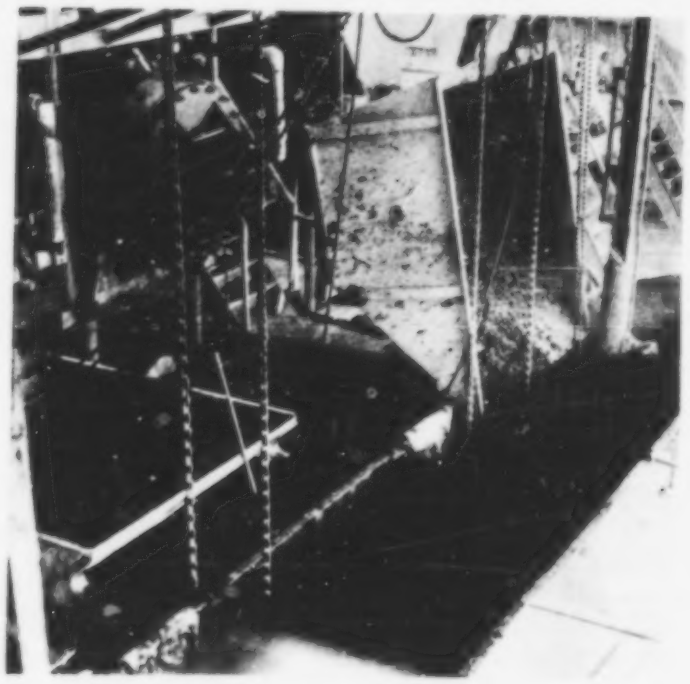


Figure 568. Tallow-laden cracklings being dumped from a percolator after free tallow has been allowed to drain (California Rendering Co., Ltd., Los Angeles, California).

Tallow from the percolators and presses is further treated to remove minor quantities of solids and water. Solids may be removed in desludging centrifuges, filters, or settling tanks. Traces of moisture are often removed from it by boiling or blowing air through heated tallow. Some operators remove moisture by settling in cone-bottom tanks, often with the aid of soda ash or sulfuric acid to provide better phase separation.

In some instances, solvents are used to extract tallow from rendered solids. Solvent extraction allows extremely fine control of products. The Belgian De Smet process, in which hexane is employed, has been adopted by some renderers in the United States and Canada. The entire process is enclosed in a vaportight building to minimize the explosion hazard. After extraction, hexane is stripped from tallow and solids. The only measurable air contaminants, solvent vapors, are vented at one or more condensers.

DRYING BLOOD

Animal blood is evaporated and thermally digested to produce a dry meal used as a fertilizer, as a livestock feed supplement, and, to a limited degree, as a glue. Blood contains only 10 to 15 percent solids and essentially no fat. At most packing houses, it is dried in horizontal, dry rendering cookers. In typical slaughtering operations, blood is continually drained from the kill floor to one or more cookers, throughout the day. Initially, while there is appreciable moisture in the blood, heat transfer through the jacket is reasonably rapid. As the moisture content decreases, however, heat transfer becomes slower. During the final portion of the cycle, drying is extremely slow, and dusty meal can be entrained in exit gases.

In some instances, a tubular evaporator is used to remove the initial portion of the water. When the moisture content decreases to about 65 percent, the material is transferred to a dry rendering cooker for final evaporation.

Some animal blood is spray dried to produce a plywood glue that commands a price considerably higher than that of fertilizer or livestock feed. This is an air-drying process, and exhaust gases are markedly more voluminous than those of rendering equipment. Feedstocks are usually concentrated in an evaporator before the spray drying.

PROCESSING FEATHERS

Poultry feathers are pressure cooked and subsequently dried to produce a high-protein meal used principally as a poultry feed supplement. Feathers, like blood, contain practically no fat, and meal is the only product of the system. Feathers are pressure cooked at about 50 psig to hydrolyze the protein keratin, their principal constituent. Initial cooking is usually carried out in a dry rendering cooker. Final moisture removal may be accomplished in the cooker at ambient pressure or in separate air-drying equipment. Rotary steamtube air driers, such as that shown in Figure 569, are frequently used for this purpose. If separate driers are employed, the material is transferred from cooker to drier at a moisture content of about 50 percent.

ROTARY AIR DRIERS

Direct-fired rotary driers are seldom used in the reduction of inedible packing house waste or dead stock. As noted previously in this chapter, they find wide use in the reduction of fish scrap. Fired driers have been used to a

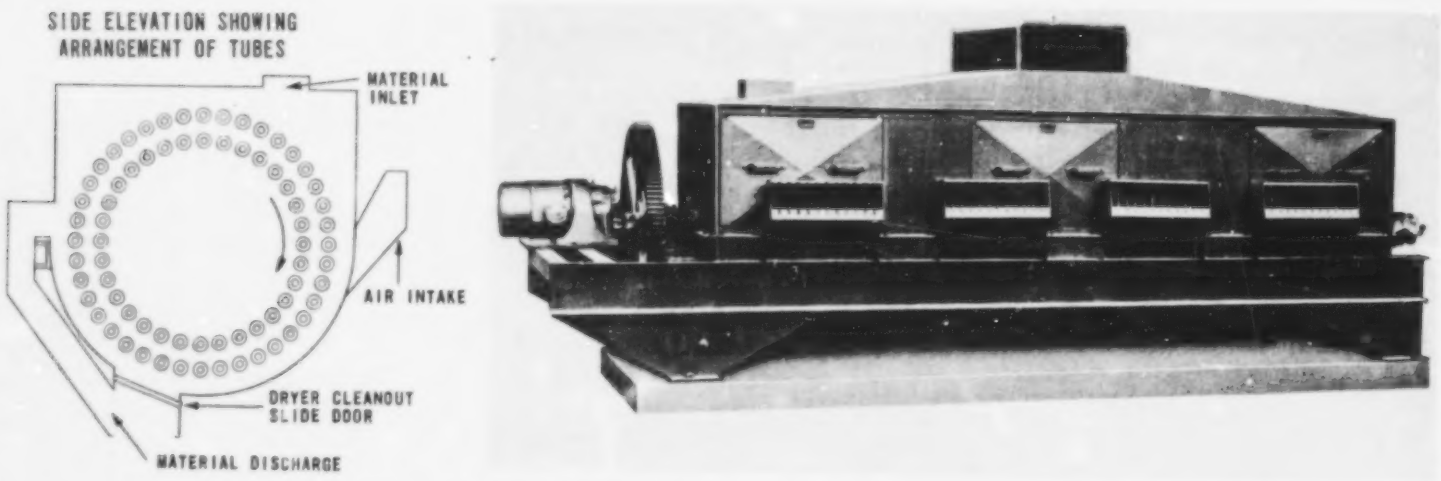


Figure 569. A rotary steamtube air drier of the type commonly used for the continuous drying of cooked feathers (The V.D. Anderson Co., Cleveland, Ohio)

limited degree to dry wet rendering tankage and some materials of low tallow content. Where air driers are required, steamtube units are generally more satisfactory from the standpoint of both product quality and odor emission.

THE AIR POLLUTION PROBLEM

Malodors are the principal air contaminants emitted from inedible-rendering equipment and from other heated animal matter reduction processes. Reduction plant odors emanate from the handling and storage of raw materials and products as well as from heated reduction processes. Some feed materials are highly decayed, even before delivery to scavenger rendering plants, and the grinding, conveying, and storage of these materials cannot help but generate some malodors. Cooking and drying processes are, nevertheless, considered the largest odor sources, and most odor control programs have been directed at them. Handling and storage odors can usually be kept to a tolerable minimum by frequently washing working surfaces and by processing uncooked feedstocks as rapidly as possible.

McCord and Witheridge (1949), who discuss the "offensive trades" at length, attribute rendering plant malodors to a variety of com-

pounds. Ronald (1935) identifies rendering odors as principally ammonia, ethylamines, and hydrogen sulfide, all decomposition products of proteins. Skatole, other amines, sulfides, and mercaptans are also usually present. Tallow and fats do not generate as great quantities of odorous materials. Aldehydes, organic acids, and other partial oxidation products are the principal odorous breakdown products of fats. Putrescine, $NH_2(CH_2)_4NH_2$, and cadaverine, $NH_2(CH_2)_5NH_2$, are two extremely malodorous diamines associated with decaying flesh and rendering plants. Several specific compounds have extremely low odor thresholds and are detectable in concentrations as small as 10 parts per billion (ppb). Odor threshold concentrations of some pertinent compounds are listed in Table 227. Many suspected compounds have not been positively identified nor have their odor thresholds been determined.

Table 227. ODOR THRESHOLD CONCENTRATIONS OF SELECTED COMPOUNDS (Dalla Valle and Dudley, 1939)

Substance	Formula	Threshold concentration,	
		mg/liter	ppm by volume
Acrolein	$CH_2{:}CH{\cdot}CHO$	0.038	16
Allyl amine	$CH_2{:}CH{\cdot}CH_2{\cdot}NH_2$	0.067	28
Allyl mercaptan[a]	$CH_2{:}CH{\cdot}CH_2{\cdot}SH$	0.00005	0.016
Ammonia	NH_3	0.037	52
Dibutyl sulfide	$(C_4H_9)_2S$	0.0011	0.180
Ethyl mercaptan[a]	C_2H_5SH	0.00019	0.072
Hydrogen sulfide	H_2S	0.0011	0.770
Oxidized oils		0.0011	--
Skatole	C_9H_8NH	0.0012	0.220
Sulfur dioxide	SO_2	0.009	3.3

[a]Average value obtained with material of varying purity.

Cookers As Prominent Odor Sources

When animal matter is subjected to heat, the cell structure breaks down liberating volatile gases and vapors. Further heating causes some chemical decomposition, and the resultant products are often highly odorous. All these malodorous gases and vapors are entrained in exhaust gases.

Exhaust products from cooking processes consist essentially of steam. Entrained gases and vapors are, nevertheless, highly odorous and apt to elicit nuisance complaints in areas surrounding animal matter reduction plants. Odor concentrations measured in exhaust gases of typical reduction processes are listed in Table 228. Evidently there is a wide variation in odor concentrations from similar equipment. For instance, dry-batch rendering processes range from 5,000 to 500,000 odor units per scf, depending principally upon the type and "ripeness" of feedstocks. Blood drying can be even more odorous, with concentrations as great as 1 million odor units per scf if the blood is allowed to age for only 24 hours before processing.

Odors From Air Driers

As can be seen from Table 228, feather drier odor concentrations, though generally smaller, are more variable than those from rendering

Table 228. ODOR CONCENTRATIONS AND EMISSION RATES FROM INEDIBLE REDUCTION PROCESSES

Source	Odor concentration, odor unit/scf		Typical moisture content of feeding stocks, %	Exhaust products, scf/ton of feed[a]	Odor emission rate, odor unit/ton of feed
	Range	Typical average			
Rendering cooker, dry-batch type[b]	5,000 to 500,000	50,000	50	20,000	$1,000 \times 10^6$
Blood cooker, dry-batch type[b]	10,000 to 1 million	100,000	90	38,000	$3,800 \times 10^6$
Feather drier, steamtube[c]	600 to 25,000	2,000	50	77,000	153×10^6
Blood spray drier[c,d]	600 to 1,000	800	60	100,000	80×10^6
Grease-drying tank, air blowing			< 5	100 scfm per tank	
156°F		4,500			
170°F		15,000			
225°F		60,000			

[a]Assuming 5 percent moisture in solid products of system.
[b]Noncondensable gases are neglected in determining emission rates.
[c]Exhaust gases are assumed to contain 25 percent moisture.
[d]Blood handled in spray drier before any appreciable decomposition occurs.

cookers. Their largest odor concentrations--25,000 odor units per scf--are associated with operations where feedstocks are putrefied or not completely cooked beforehand or where the meal is overheated in the drier. Under optimum conditions, odor concentrations from these driers should not exceed 2,000 odor units per scf. With blood spray driers, where extreme care is maintained to ensure freshness of feedstocks, concentrations can be less than 1,000 odor units per scf. In general, air drier odor concentrations are less than those of cookers for the following reasons: (1) In most instances feedstocks are cooked or partially evaporated before the air drying; (2) odorous gases are more dilute in drier exit gases; (3) feedstocks are often fresher.

Odors and Dust From Rendered-Product Systems

Some odors and dust are emitted from cooked animal matter as it is separated and refined. The heaviest points of odor emission are the percolators into which hot cooker contents are dumped. Steam and odors evolve from the hot material, particularly during times of cooker unloading. Cookers are normally dumped at or near 212°F. Lesser volumes of steam and odors are generated at presses, centrifuges, and settling tanks where meal and tallow are heated slightly to effect the desired separation.

The grinding of pressed solids, and subsequent meal conveying are the only points of dust emission from rendering systems. These particulates are reasonably coarse, and dust is usually not excessive.

Grease-Processing Odors

Some odors are generated at processing tanks when moisture is removed from grease or tallow by boiling or by air blowing or both. If air is used for this purpose, exhaust volumes seldom exceed 100 scfm, but odor concentrations are measurable. Odor concentration is a function of operating temperature. As shown in Table 228, measured concentrations have been found to range from 4,500 odor units per scf at 150°F, to 60,000 odor units per scf at 225°F. Odor concentrations vary greatly with the type of grease processed and the air rate, as well as with temperature.

Raw-Materials Odors

Some malodors emanate from the cutting and handling of raw materials. In most instances these emissions are not great. Odors usually originate at the point where raw material is first sliced, ground, or otherwise broken into smaller parts. Most feedstocks are ground in a hammer mill before the cooking. Large, whole animals (dead stock) must be skinned, eviscerated, and at least partially dismembered before being fed to rendering equipment. If the animal is badly decomposed, this skinning and cutting operation can evolve strong odors.

HOODING AND VENTILATION REQUIREMENTS

All heated animal matter reduction processes should be vented directly to control equipment. Hooding is used in some instances to collect malodors generated in the processing of raw materials and cooked products.

If highly decayed dead stock is being processed, the entire dead stock room should be ventilated at a rate of 40 or more air changes per hour for worker comfort. Areas should also be ventilated where raw materials are stored unrefrigerated for any appreciable time before processing.

Hooding may be employed on raw-material grinders preceding cookers and percolator pans and expeller presses used to handle cooked products. Although the volume of steam and odors evolved at any of these points does not exceed 100 cfm, greater volumes are normally required to offset crossdrafts. Indraft velocities of 100 fpm under hoods are usually satisfactory.

Emission Rates From Cookers

The ventilation rates of cookers can be estimated directly from the quantity of moisture removed and the time of removal. Maximum emission rates from dry cookers are approximately twice the average moisture evaporation rates. In the determination of exhaust volumes, noncondensable gases can normally be neglected. Consider a batch cooker that removes 3,000 pounds of moisture from 6,000 pounds of animal matter in 3 hours, a relatively long cook cycle. The average rate of emission is 16.7 pounds per minute or 450 cfm steam at about 212°F. The instantaneous evaporation rate and cumulative moisture removal are plotted in Figure 570. The maximum evolution rate apparently occurs near the initial portion of the cook at 29 pounds per minute or 790 cfm at 212°F. As moisture is removed from a batch cooker, the heat transfer rate decreases, the temperatures rise, and the evaporation rate falls off. The general shapes of the curves in Figure 570 are typical of batch-cooking cycles. Where cook times are appreciably shorter, evaporation rates are greater; nevertheless, the ratio of maximum to average evaporation rate is maintained at approximately 2 to 1.

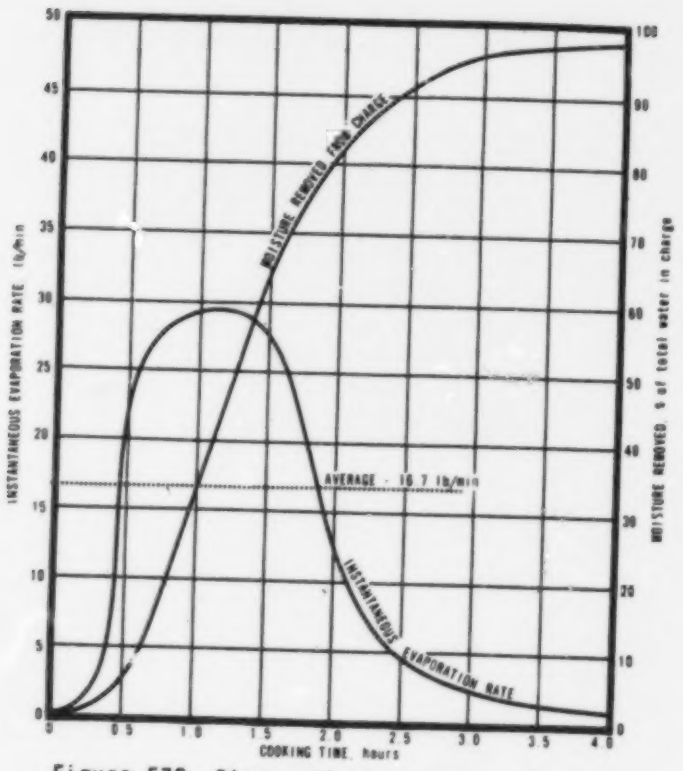

INSTANTANEOUS EVAPORATION RATE lb/min
MOISTURE REMOVED, % of total water in charge
COOKING TIME, hours
MOISTURE REMOVED FROM CHARGE
AVERAGE - 16.7 lb/min
INSTANTANEOUS EVAPORATION RATE

Figure 570. Steam emission pattern from a batch-type, dry rendering cooker operated at ambient pressure.

The length of a cooking cycle, and the evaporation rate are dependent upon the temperature in the steam jacket, and the rotational speed of the agitator. The highest permissible agitator speeds (about 65 rpm) can result in cooking times of 45 minutes to 1 hour. Many operators, particularly at packing houses, use slower agitator speeds, and cycles are as long as 4 hours.

If vacuum cooking is employed, volume rates and temperatures decrease as the batch progresses. With these systems, the vacuum-producing devices largely govern cooking times. The evaporation rate in a vacuum system is limited by the rate at which steam can be removed, usually by condensation. If vapor cannot be condensed as fast as it is evaporated, the cycle is merely lengthened.

Pressure cookers have a slightly different emission pattern, but maximum emission rates are again twice the average. During the initial portion of the cycle, there are no emissions while pressures are increasing to the desired maximum. The cooker is vented at elevated pressure, usually about 50 psig. High-pressure vapors are relieved through small bypass lines so that the surge of steam is not more than the control system can handle. Most of the contained moisture is evaporated after pressures are reduced to ambient levels.

Vapor emission rates from wet rendering cookers are considerably lower than those from dry cookers, comparable to initial volumes during pressure cooking. Only enough steam is flash evaporated to reduce the pressure to 1 atmosphere. The large percentage of moisture in a wet rendering process is removed as water by physical separation rather than by evaporation.

Emission rates from continuous, dry rendering processes are steady and can be calculated directly from the moisture content of feedstocks and products. To lower the moisture content from 50 to 5 percent in typical meat and bone scrap, 1,670 scfm or 79 pounds of steam per minute would be evaporated if the charge rate to the cooker were 10,000 pounds per hour.

Emission rates from blood cookers are generally lower than those from dry rendering cookers owing to the longer cook cycles employed. Blood is continually added to an operating cooker during a typical packinghouse workday. The emission rate fluctuates as a function of the moisture content in the cooker. A cook cycle may extend over 8 or 10 hours, and charging patterns can vary tremendously. Emission rates do not normally exceed 500 cfm, and at times, are considerably lower.

Emission rates from feather cookers follow the same pattern as those from other dry pressure cookers though rates are lower and cooking times usually longer. Inasmuch as feathers contain no appreciable tallow, heat transfer is relatively slow. At some plants, batches of feathers are cooked as long as 8 hours. Where separate driers are used, feathers are still cooked 2 to 4 hours, which reduces the moisture content to 50 percent before the charging to a drier.

Emission Rates From Driers

Most air-drying processes are operated on a continuous basis with no measurable fluctuations in exhaust rates. Enough air and, in some instances, products of combustion are added to yield a moisture content of 10 to 30 percent by volume in the exit gas stream. To dry 2,000 pounds of cooked feathers per hour from 50 to 5 percent moisture requires a drier (steamtube) exhaust volume of 1,660 scfm at 20 percent moisture in the gases. Volumes from air driers are always much greater than those from cooking processes, and they contain far greater quantities of noncondensable gases.

AIR POLLUTION CONTROL EQUIPMENT

The principal devices used to control reduction plant odors are afterburners and condensers, installed separately and in combination. Adsorbers and scrubbers also find use. Dust is not a major problem at animal matter reduction plants, and simple cyclones are usually sufficient to prevent excessive emissions.

Selection of odor control equipment is influenced greatly by the moisture content of the malodorous stream, or conversely, by the percentage of noncondensable gases. It is usually more costly to control noncondensable gases than moisture. Reduction plant exhaust streams fall into two general types: (1) Those consisting almost entirely (95 percent or greater) of water vapor, as from rendering cookers and blood cookers, and (2) air drier exhaust gases, which seldom contain more than 30 percent moisture by volume.

Controlling High-Moisture Streams

Condensing moisture from wet cooker gases is almost always economically attractive. Some malodors are usually condensed or dissolved in the condensate. In any case the volume is reduced by a factor of 10 or more. The remaining noxious gases can be directed to a further control device such as an afterburner or carbon adsorber before being vented to the atmosphere.

Selection of the condenser depends upon the particular facilities of the operator. The principal types of condensers noted in Chapter 5 are adaptable to reduction cooker exhaust streams. Contact condensers and air-cooled and water-cooled surface condensers have been successfully used for this purpose.

Contact condensers are more efficient control devices than surface condensers are, though both types are highly effective when coupled with an afterburner or carbon adsorber. This is illustrated by data in Table 229. Odor concentrations are seen to be considerably greater in gases from surface condensers than in those from contact condensers. With condensate at 80°F, a contact condenser reduces odor concentrations by about 80 percent and odor emission rates by 99 percent. At the same condensate temperature, odor concentrations increase across a surface condenser. Either type of condenser, however, reduces the volume of cooker vapors by 95 percent or more. Thus, even a surface condenser lowers the odor emission rate by about 50 percent.

Contact condensers are relatively inexpensive to install but require large quantities of one-pass cooling water. From 15 to 20 pounds of cooling water is necessary to condense and subcool adequately 1 pound of steam. Since cooling water and condensate are intimately mixed, the resultant liquid cannot be cooled in an atmospheric cooling tower without emission of malodors to the atmosphere. The large condensate volume that must be disposed of can overload sewer facilities in reduction plant areas.

Subcooling Condensate

Surface condensers, whether air cooled or water cooled, should be designed to provide subcooling

Table 229. ODOR REMOVAL EFFICIENCIES OF CONDENSERS OR AFTERBURNERS, OR BOTH, VENTING A TYPICAL DRY RENDERING COOKER[a]
(Calculated from Mills et al., 1963)

Odors from cookers		Condenser type	Condensate temperature, °F	Afterburner temperature, °F	Odors from control system		Odor removal efficiency, %
Concentration, odor units/scf	Emission rate, odor units/min				Concentration, odors units/scf	Modal emission rate, odor units/min	
50,000	25,000,000	None	--	1,200	100 to 150 (Mode 120)	90,000	99.40
		Surface	80	None	100,000 to 10 million (Mode 500,000)	12,500,000	50
		Surface	140	1,200	50 to 100 (Mode 75)	6,000	99.98
		Contact	80	None	2,000 to 20,000 (Mode 10,000)	250,000	99
		Contact	140	1,200	20 to 50 (Mode 25)	2,000	99.99

[a] Based on a hypothetical cooker that emits 500 scfm of vapor containing 5 percent noncondensable gases.

of condensate to 140°F or lower. This may be accomplished in several ways, as noted in Chapter 5. The need for subcooling is negated when high vacuum is employed. With vacuum operation, volatile, malodorous gases are drawn off through the ejector or vacuum pump, and condensation temperatures are often less than 140°F. At a vacuum of 24 inches of mercury (2.9 psia), the condensation temperature of steam is 140°F.

Condenser Tube Materials

Reduction process vapors can be highly corrosive to the metals commonly used in surface condenser tubes. Both acid and alkaline vapors can be present, sometimes alternately in the same equipment. Vapors from relatively fresh meat and bone scrap rendering are mildly acidic, and some brasses are satisfactory. Brasses fail rapidly, however, under alkaline conditions. Mild steel tubes are adequate where the pH is greater than 7.0 but quickly corrode under acid conditions.

Some operations, such as dead stock rendering, can produce alkaline and acid gases alternately during the cook cycle. Here neither brass nor mild steel is satisfactory. In these cases, stainless steels have been successfully employed. With a relatively constant pH condition, less expensive metals could be used.

Where acid-base conditions are uncertain, a pH determination should be made. The vapors should be sampled over the complete process cycle with all representative feedstocks in the cookers.

Interceptors in Cooker Vent Lines

Air pollution control systems venting cookers should be equipped with interceptor traps to prevent fouling of condensers and other control devices. So-called wild blows are relatively common in dry rendering operations. They result from momentary plugging of the cooker vent. Steam pressures increase until they are sufficient to unblock the line. In the unblocking, a measurable quantity of animal matter is forced through the vent line at high velocity. If there is no interceptor, this material fouls condensers, hot wells, afterburners, and other connected control devices. Although a wild blow is an operational problem, it greatly affects the efficiency of odor control equipment.

The systems shown in Figures 571 and 572 include interceptors in the vent lines between the cookers and condensers. The installation depicted in Figure 572 uses an air-cooled con-

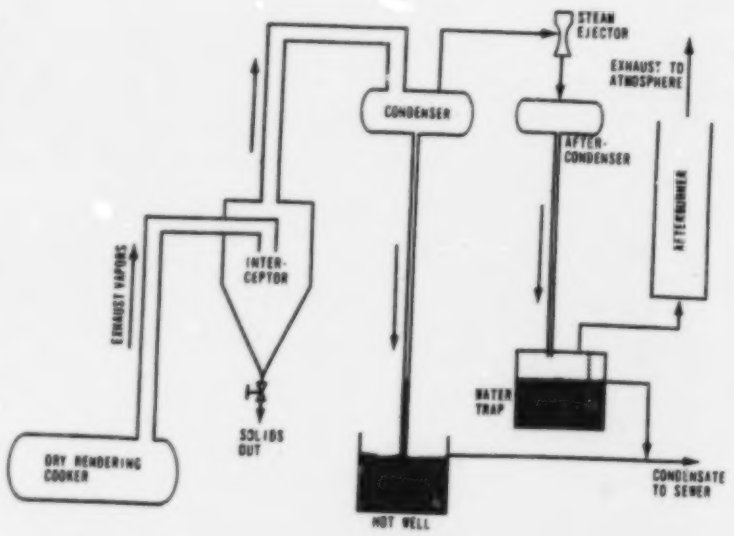


Figure 571. A condenser-afterburner control system with an interceptor located between the rendering cooker and condenser.

denser and afterburner. Most tanks are of sufficient size to hold approximately one-half of a full cooker charge. They are designed so that collected materials can be drained while the cooker and control system are in operation.

Vapor Incineration

For animal matter reduction processes, as with most odor sources, flame incineration is the most positive control method. Afterburners have been used individually and in combination with other devices, principally condensers. Rule 64 of the Los Angeles County Air Pollution Control District (see Appendix A), which specifically governs heated animal matter reduction processes, uses incineration at 1,200°F as an odor control standard. Any control method or device as effective as flame incineration at 1,200°F is acceptable under the regulation.

Total incineration is used to control low-moisture reduction process streams, as from driers, and various other streams of small volume. At reduction plants, steamtube driers are normally the largest equipment controlled in this manner. Gases from the driers are vented directly to afterburners, which are operated at temperatures of 1,200°F or higher. Dust is usually not in sufficient concentration to impede incineration. If there is appreciable particulate matter in the gas stream, auxiliary dust collectors must be installed or the afterburner must be operated at 1,600°F or higher. At 1,200°F, solids are only partially incinerated.

Flame incineration at 1,200°F reduces odor concentrations from steamtube driers to 100 to 150

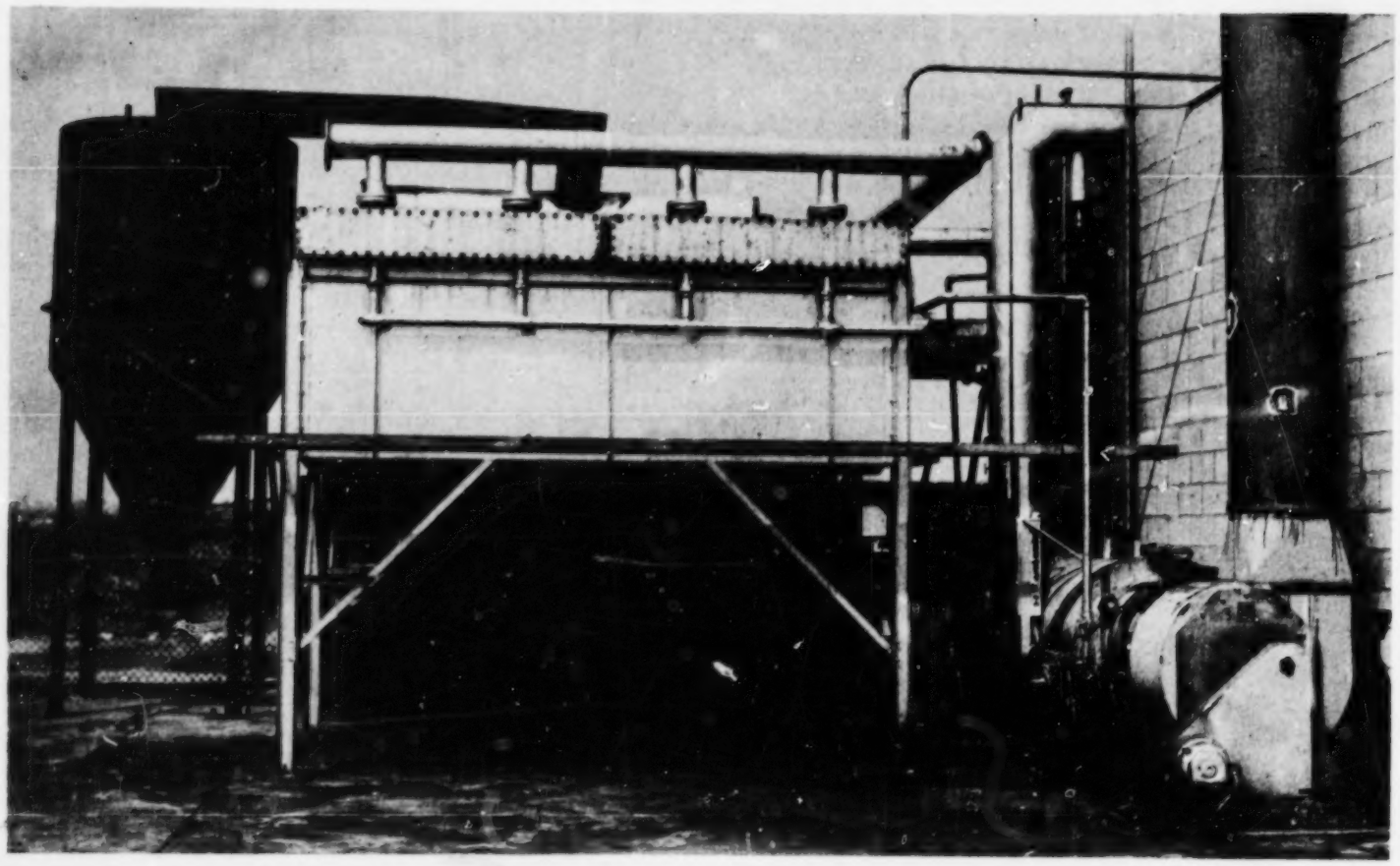


Figure 572. A cooker control system including an interceptor, air-cooled condenser, and afterburner (California Protein Products, Los Angeles, Calif.).

odor units per scf where dust loading is not excessive. Some variation can be expected when concentrations are greatly in excess of the nominal 2,000 odor units per scf usually encountered in drier gases.

Because of the large volumes exhausted from driers, afterburner fuel requirements are a major consideration. A drier emitting 3,000 scfm requires about 4,800 scfh natural gas for 1,200°F incineration. Several means of recovering waste heat from large afterburner streams have been used. The most common are the generation of steam and preheating of drier inlet gases.

In the control of spray driers, dust collectors must often be employed ahead of the afterburner. High-efficiency centrifugal collectors, baghouses, or precipitators may be required as precleaners, depending upon the size and concentration of particulates.

Condensation–Incineration Systems

As noted earlier, wet cooker vapors are seldom incinerated in toto. While 100 percent incineration is feasible, operating costs are much greater than for condenser-afterburner combinations. Both types of control systems provide better than 99 percent odor removal, but the combination system results in a much lower odor emission rate.

The cooker control systems shown in Figures 571 and 572 and in Chapter 5, illustrate typical combinations of condensers and afterburners. Uncondensed gases are separated from condensate at either the condenser or hot well. Gases enter the afterburner near ambient temperature. Either contact or surface condensers serve to remove essentially all particulates. The remaining "clean" uncondensed gases can be readily incinerated at 1,200°F. In some instances there are minor concentrations of methane and other fuel gases in the stream. Uncondensed gases from surface condensers are richer in combustibles than are those from contact condensers. As shown in Table 229, odor removal efficiencies greater than 99.9 percent are possible with condenser-afterburner systems serving dry rendering cookers.

When the moisture content of the contaminated stream is from 15 to 40 percent, the use of condensers may or may not be advantageous. In these cases, a number of factors must be weighed including volumes, exit temperatures, fuel costs, water availability, and equipment costs among others.

Incineration is not required with some condenser installations. An afterburner or equally effective device should always be employed to eliminate the heavy concentrations of malodors vented from surface condensers. With contact condensers, however, adequate control can be effected if condensate temperatures are sufficiently low. The data in Table 229 show that a contact condenser operating at 80°F provides about 99 percent control of cooker odors. When there are appreciable uncondensed gases or when condensate temperatures are greater than approximately 140°F, the additional control and insurance afforded by incineration may be mandatory.

Carbon Adsorption of Odors

Most of the malodorous gases emitted from reduction processes can be adsorbed on activated carbon to some degree. The capacities of activated carbons for hydrogen sulfide, uric acid, skatole, putrescine, and several other specific compounds found in reduction plant gases are considered "satisfactory" to "high." For ammonia and low-molecular-weight amines, they have somewhat lower capacities. The latter compounds tend to be desorbed as the carbon becomes saturated with high-molecular-weight compounds (Barnebey-Cheney Co., Bulletin T-642). For the mixture of malodorous materials encountered at reduction plants, a high-quality carbon would be expected to adsorb from 10 to 25 percent of its weight before the breakthrough point is reached.

Carbon adsorbers are as efficient as afterburners but have limitations that often make them unattractive for cooker control. Their most useful application is the control of large volumes of relatively cool and dry gases. Adsorbers usually cannot be employed in reduction process streams without auxiliary dust collectors, condensers, or coolers.

Carbon adsorbers cannot be used to control emissions from wet cookers unless the adsorbers are preceded by condensers. Activated carbon does not adsorb satisfactorily at temperatures greater than 120°F. To cool cooker vapors, which are predominantly steam, to this temperature, most of the moisture must be recovered. At 120°F, saturated air contains only 11.5 percent water vapor by volume. Condenser-adsorber systems are reported to remove odors as efficiently as condenser-afterburner systems. No comparative odor concentration data are available.

Drier exhaust streams can be controlled with adsorbers if inlet temperatures and dust concentrations can be held sufficiently low and small, respectively. Many driers are exhausted at temperatures higher than 200°F and contain enough fine particulates to foul adsorbers. A scrubber-contact condenser is often a satisfactory means of removing particulates and lowering temperatures before adsorption. If, however, there are appreciable particulates of less than 10 microns diameter, more efficient dust control devices are necessary.

Regeneration of activated carbon is a major consideration at animal matter reduction plants. Carbon life between regenerations can be as short as 24 hours, particularly where malodors are in heavy concentration, and the carbon has a low capacity for the compounds being adsorbed. Regeneration frequency is a function of many factors, including malodor concentration, the quality and quantity of carbon, and the kind of compounds that must be adsorbed.

Some means must be employed to contain or destroy the desorbed gases; otherwise, malodors are vented to the atmosphere in essentially the same form that they were collected. Incineration at 1,200°F or higher is the most common method of controlling these gases. For streams of low volume, afterburners used during regeneration can be as large and as costly as those used to incinerate odors from the basic reduction equipment. The need for incineration of desorbed gases usually offsets the advantages of carbon adsorption for streams of low volume. If the exhaust rate is sufficiently small, incinerating vapors directly, as they are evolved from the reduction equipment or condenser, is considerably simpler.

Odor Scrubbers

Conventional scrubbers are seldom used to control reduction process odors. Of course, contact condensers provide some scrubbing of cooker gases; nevertheless, these devices are principally condensers, and tail waters cannot be recirculated. It is conceivable that alkaline or acid scrubbers would be effective for drier gases if all the odorous compounds reacted in the same manner. Unfortunately, the malodorous mixtures encountered in typical reduction processes are not homogenous from the acid-base standpoint.

Strong oxidizing solutions, such as chlorine dioxide, are reported to destroy many of the odorous organic materials (Woodward and Fenrich, 1952). With any type of recirculating chemical scrubber, the contaminated stream would first have to be cooled to ambient temperature, by condensation if necessary.

Odor Masking and Counteraction

Masking agents and odor counteractants have been used with some success to offset in-plant odors. These materials are added to cooker feedstocks and sprayed in processing and storage areas. They are reported to provide a degree of nuisance elimination and worker comfort, particularly in high-odor areas such as dead stock skinning rooms. Masking agents and counteractants, however, are not recommended for the control of odors from heated animal matter reduction equipment.

ELECTROPLATING

Electroplating is a process used to deposit, or plate, a coating of metal upon the surface of another metal by electrochemical reactions. In variations of this process, nonmetallic surfaces have been plated with metals, and a nonmetal such as rubber has been used as a plating material. Industrial and commercial applications of electroplating are numerous, ranging from manufactured parts for automobiles, tools, other hardware, and furniture to toys. Brass, bronze, chromium (chrome), copper, cadmium, iron, lead, nickel, tin, zinc, and the precious metals are most commonly electroplated.

Platings are applied to decorate, to reduce corrosion, to improve wearing qualities and other mechanical properties, or to serve as a base for subsequent plating with another metal. The purpose and type of plating determine the details of the process employed and, indirectly, the air pollution potential, which is a function of the type and rate of "gassing," or release of gas bubbles from plating solutions with entrainment of droplets of solution as a mist. The degree of severity of air pollution from these processes may vary from being an insignificant problem to a nuisance.

An electroplating system consists of two electrodes--an anode and a cathode--immersed in an electrolyte and connected to an external source of direct-current electricity. The base material upon which the plating is to be deposited makes up the cathode. In most electroplating systems, a bar of the metal to be deposited is used as the anode. The electrolyte is a solution containing: (1) Ions of the metal to be deposited and (2) additional dissolved materials to aid in electrical conductivity and produce desirable characteristics in the deposited plating.

When an electric current is passed through the electrolyte, ions from the electrolyte are reduced, or deposited, at the cathode, and an equivalent amount of either the same or a different element is oxidized or dissolved at the anode. In some systems, for example, chrome plating, the deposited metal does not dissolve at the anode, and hence, insoluble anodes are used, the source of the deposited metal being ions formed from salts of that metal previously dissolved in the electrolyte.

The character of the deposited metal is affected by many factors, including the pH of the electrolyte, the metallic ion concentration, the simplicity or complexity of the metallic ion (including its primary and secondary ionization products), the anodic and cathodic current densities, the temperature of the electrolyte, and the presence of modifying or "addition agents." By varying these factors, the deposit can be varied from a rough, granular, loosely adherent plating to a strong, adherent, mirror-finish plating. If the electromotive force used is greater than that needed to deposit the metal, hydrogen is also formed at the cathode, and oxygen forms at the anode. When insoluble anodes are used, oxygen or a halogen (if halide salts are used in the electrolyte) is formed at the anode. Both of these situations produce gassing.

A potential air pollution problem can also occur in the preparation of articles for plating. These procedures, primarily cleaning processes, are as important as the plating operation itself for the production of high-quality finishes of impervious, adherent metal coatings. The cleaning of metals before electroplating generally requires a multistage procedure as follows:

1. Precleaning by vapor degreasing or by soaking in a solvent, an emulsifiable solvent, or an emulsion (used for heavily soiled items);

2. intermediate cleaning with an alkaline bath soak treatment;

3. electrocleaning with an alkaline anodic or cathodic bath treatment, or both (the chemical and mechanical [gassing] action created by passing a current through the bath between the immersed article and an electrode produces the cleaning);

4. pickling with an acid bath soak treatment, with or without electricity.

The selection of an appropriate cleaning method in any given case depends upon three important factors: The type and quantity of the soil, composition and surface texture of the base metal, and the degree of cleanliness required. In general, oil, grease, and loose dirt are removed first; then scale is removed, and, just before the plating, the pickling process is employed. The articles to be plated are thoroughly rinsed after each treatment to keep them from contaminating succeeding baths. A cold rinse is usually used after the pickling to keep the articles from drying before their immersion in the plating bath. Electrocleaning and electropickling are generally faster than similar soak procedures; however, the electroprocesses always produce more gassing (hydrogen at the cathode and oxygen at the anode) than the nonelectroprocesses. The gassing from cleaning solutions tends to create mists that may but usually do not, cause significant air pollution problems.

THE AIR POLLUTION PROBLEM

The electrolytic processes do not operate with 100 percent efficiency, and some of the current decomposes water in the bath, evolving hydrogen and oxygen gases. In fact, the chief advantage of electrocleaning is the mechanical action produced by the vigorous evolution of hydrogen at the cathode, which tends to lift off films of oil, grease, paint, and dirt. The rate of gassing varies widely with the individual process. If the gassing rate is high, entrained mists of acids, alkaline materials, or other bath constituents are discharged to the atmosphere.

Most of the electrolytic plating and cleaning processes are of little interest from a standpoint of air pollution because the emissions are inoffensive and of negligible volume, owing to low gassing rates. Generally, air pollution control equipment is not required for any of these processes except the chromium-plating process. In this process, large volumes of hydrogen and oxygen gases are evolved. The bubbles rise and break the surface with considerable energy, entraining chromic acid mist, which is discharged to the atmosphere. Chromic acid mist is very toxic and corrosive and its discharge to the atmosphere should be prevented.

Chromic acid emissions have caused numerous nuisance complaints and frequently cause property damage. Particularly vulnerable are automobiles parked downwind of chrome-plating installations. The acid mist spots car finishes severely. The amounts of acid involved are relatively small but are sufficient to cause damage. In a typical decorative chromium-plating installation with an exhaust system but without mist control equipment, a stack test disclosed that 0.45 pound of chromic acid per hour was being discharged from a 1,300-gallon tank.

Chromium-plating processes can be divided into two general classes, one of which offers a considerably greater air pollution problem than the other. "Hard chrome" plating, which causes the more severe problem, produces a thick, hard, smooth, corrosion-resistant coating. This plating process requires a current density of about 250 amperes per square foot, which results in a high rate of gassing and a heavy evolution of acid mist. The less severe problem is presented by the process called "decorative chrome" plating, which requires a current density of only about 100 amperes per square foot and results in a definitely lower gassing rate.

HOODING AND VENTILATING REQUIREMENTS

Local exhaust systems are installed on many electroplating tanks to reduce the concentrations of steam, gases, and mists to what are commonly accepted as safe amounts for personnel in the plating room. In the past, these exhaust systems were often omitted altogether, and the resulting working conditions were often unhealthful.

In 1951, the American Standards Association introduced Code Z9.1 for Ventilation and Operation of Open Surface Tanks. This code is an organized engineering approach designed to replace the rule-of-thumb methods applied in the past. The use of this code in designing plating tank exhaust systems is recommended by public health officials and industrial hygienists.

Most exhaust systems use slot hoods to capture the mists discharged from the plating solutions. These hoods have been found satisfactory when properly designed. To obtain adequate distribution of ventilation along the entire length of the slot hood, the slot velocity should be high, 2,000 fpm or more, and the plenum velocity should be one-half of the slot velocity or less. With hoods over 10 feet in length, either multiple takeoffs or splitter vanes are needed. Enough takeoffs or splitter vanes should be used to reduce the length of the slot to sections not more than 10 feet long.

Ventilation rates for tanks, as previously discussed in Chapter 3, are for tanks located in areas having no crossdrafts. In drafty areas,

ventilation rates must be increased and baffles should be used to shield the tank.

AIR POLLUTION CONTROL EQUIPMENT

Scrubbers

The device most commonly used to control air contaminants in hard-chrome-plating tank exhaust gases is a wet collector. This type of equipment is also suitable for controlling mists from any other type of plating or cleaning tank that may cause a problem. Figure 573 shows a ventilation system with a spray-type scrubber used to control mists from two 18-foot chromc-plating tanks. Many other types of commercial wet collectors are available, constructed of various corrosion-resistant materials. Water circulation rates are usually 10 to 12 gpm per 1,000 cfm. If the water is recirculated, the makeup rate is about 2.5 to 4 gph per 1,000 cfm.

The scrubber water, of course, becomes contaminated with the acid discharged from the plating tank; therefore, efficient mist eliminators must be used in the scrubber to prevent a contaminated water mist from discharging to the atmosphere.

The scrubber water is commonly used for plating tank makeup. This procedure not only removes the acid from the scrubber but also reduces the amount of makeup acid needed for the plating solution. In some scrubbers, a very small quantity of fresh water is used to collect the acid mist; the resulting solution is continuously drained from the scrubber either into the plating tank or into a holding tank, from which it can be taken for plating solution makeup.

The mists collected by the air pollution control system are corrosive to iron or steel; therefore, hood, ducts, and scrubbers of these materials must be lined with, or replaced by, corrosion-resistant materials. Steel ducts and scrubbers lined with materials such as polyvinyl chloride have been found to resist adequately the corrosive action of the mists. In recent years, hoods, ducts, and scrubbers made entirely of polyester resins reinforced with glass fibers have been used in air pollution control systems handling acid or alkaline solutions. These systems have been found to be very resistant to the corrosive effects of plating solutions.

The scrubber removes chromic acid mist with high efficiency. A commonly used field method of determining chromic acid mist evolution consists of holding a sheet of white paper over the surface of the tank or scrubber discharge. Any mist contacting the paper immediately stains it. A piece of paper held in the discharge of a well-designed scrubber shows no signs of staining.

Figure 573. Two control systems with scrubbers venting four chrome-plating tanks. Each scrubber vents two tanks (Industrial Systems, Inc., South Gate, Calif.).

Mist Inhibitors

The mist emissions from a decorative-chrome-plating tank and from other tanks with lesser mist problems can be substantially eliminated by adding a suitable surface-active agent to the plating solutions. The action of the surface-active agent reduces the surface tension, which, in turn, reduces the size of the hydrogen bubbles. Their rates of rise, and the energy of their evolution are greatly reduced, and the amount of mist is also greatly reduced. Several of these mist inhibitors are commercially available.

If the proper concentration of mist inhibitor is maintained, a sheet of paper placed 1 inch above the bath surface shows no spotting.

INSECTICIDE MANUFACTURE

The innumerable substances used commercially as insecticides can be conveniently classified according to method of action, namely: (1) Stomach poisons, which act in the digestive system; (2) contact poisons, which act by direct external contact with the insect at some stage of its life cycle; and (3) fumigants, which attack the respiratory system.

A few of the commonly used insecticides, classified according to method of action, are shown in Table 230. The classification is somewhat arbitrary in that many poisons, such as nicotine, possess the characteristics of two or three classes.

Table 230. SOME COMMON INSECTICIDES CLASSIFIED ACCORDING TO METHOD OF ACTION

Stomach poisons	Contact poisons	Fumigants
Paris green	DDT	Sulfur dioxide
Lead arsenate	Pyrethrum	Nicotine
Calcium arsenate	Sulfur	Hydrocyanic acid
Sodium fluoride	Lime-sulfur	Naphthalene
Cryolite	Nicotine sulfate	P-dichloro-benzene
Rotenone	Methoxychlor	Ethylene oxide

Human threshold limit values of various insecticides are shown in Table 231. They represent conditions under which it is believed that nearly all workers may be repeatedly exposed day after day, without adverse effect. The amount by which these figures may be exceeded for short periods without injury to health depends upon factors such as (1) the nature of the contaminant, (2) whether large concentrations over short periods produce acute poisoning, (3) whether the effects are cumulative, (4) the frequency with which large concentrations occur, and (5) the duration of these periods.

METHODS OF PRODUCTION

Production of the toxic substances used in insecticides involves the same operations employed for general chemical processing. Similarly, chemical-processing equipment, that is, reaction kettles, filters, heat exchangers, and so forth, are the same as discussed in other sections of this chapter. Emphasis is given, therefore, to the equipment and techniques encountered in the compounding and blending of commercial insecticides to achieve specific chemical and physical properties.

Most commercial insecticides are used as either dusts or sprays. Insecticides employed as dusts are in the solid state in the 0.5- to 10-micron size range. Insecticides employed as sprays may be manufactured and sold as either solids or liquids. The solids are designed to go into solution in an appropriate solvent or to form a colloidal suspension; liquids may be either solutions or water base emulsions. No matter what physical state or form is involved, insecticides are usually a blend of several ingredients in order to achieve desirable characteristics. A convenient means of classifying equipment and their related processing techniques is to differentiate them by the state of the end product. Equipment used to process insecticides where the end product is a solid is designated solid-insecticide-processing equipment. Equipment used to process insecticides where the end product is a liquid is designated as liquid-insecticide-processing equipment.

Solid-Insecticide Production Methods

Solid mixtures of insecticides may be compounded by either (1) adding the toxicant in liquid state to a dust mixture or (2) adding a solid toxicant to the dust mixture.

Figure 574 illustrates equipment used if the toxicant in liquid state is sprayed into a dust mixture during the blending process. After leaving the rotary sifter, the solid raw materials are carried by elevator to the upper mixer where the liquid toxicant is introduced by means of spray nozzles. This particular unit has discharge gates at each end of the upper mixer, which permit the wetted mixture to be introduced either directly into the second mixer or into the high-speed fine-grinding pulverizer and then into the second mixer. From the second mixer, a discharge gate with a built-in feeder screw conveys the mixture to a second elevator for transfer to the holding bin where the finished batch is available for packaging. Although as much as 50 percent by weight of liquid toxicant may be added to the blend, the di-

Table 231. THRESHOLD LIMIT VALUES OF VARIOUS INSECTICIDES

Substance	Threshold limit value, mg/meter^3
Aldrin (1, 2, 3, 4, 10, 10-hexachloro-1, 4, 4a, 5, 8, 8a-hexahydro-1, 4, 5, 8-dimethanonaphthalene)	0.25
Arsenic	0.5
Calcium arsenate	1
Chlordane (1, 2, 4, 5, 6, 7, 8, 8-octachloro-3a, 4, 7, 7a-tetrahydro-4, 7-methanoindane)	0.5
Chlorinated camphene, 60%	0.5
2, 4-D (2, 4-dichlorophenoxyacetic acid	10
DDT (2, 2-bis(p-chlorophenyl) -1, 1, 1-trichloroethane)	1
Dieldrin (1, 2, 3, 4, 10, 10-hexachloro-6, 7, epoxy-1, 4, 4a, 5, 6, 7, 8, 8a-octahydro-1, 4, 5, 8-dimethano-naphthalene)	0.25
Dinitro-o-cresol	0.2
EPN (O-ethyl O-p-nitrophenyl thionobenzenephosphonate)	0.5
Ferbam (ferric dimethyl dithiocarbamate)	15
Lead arsenate	0.15
Lindane (hexachlorocyclohexane gamma isomer)	0.5
Malathion (O, O-dimethyl dithiophosphate of diethyl mercaptosuccinate)	15
Methoxychlor (2, 2-di-p-methoxyphenyl-1, 1, 1-trichloroethane)	15
Nicotine	0.5
Parathion (O, O-diethyl-O-p-nitrophenyl thiophosphate)	0.1
Pentachlorophenol	0.5
Phosphorus pentasulfide	1
Picric acid	0.1
Pyrethrum	5
Rotenone	5
TEDP (tetraethyl dithionopyrophosphate)	0.2
TEPP (tetraethyl pyrophosphate)	0.05
Thiram (tetramethyl thiuram disulfide)	5
Warfarin (3-(a-acetonylbenzyl) 4-hydroxycoumarin)	0.1

luent clays are porous and absorb the liquid to such a degree that the ingredients of the mix are essentially solids and act as such. In insecticide processing, the type of mixer generally employed to blend liquids with dusts is the ribbon blender.

Figure 575 is an illustration of a ribbon blender screw. This screw consists of two or more ribbon flights of different diameters and opposite hand, mounted one within the other on the same shaft by rigid supporting lugs. Ingredients of the mix are moved forward by one flight and back by the other, which thereby induces positive and thorough mixing with a gradual propulsion of the mixed material to the discharge.

An example of an insecticide compound produced by this method is toxaphene dust. A commonly used formulation is:

	%
Toxaphene (chlorinated camphene)	40
Kerosine	4.5
Finely divided porous clay	55.5

The toxaphene is melted and mixed with the kerosine, then sprayed into the clay and thoroughly blended.

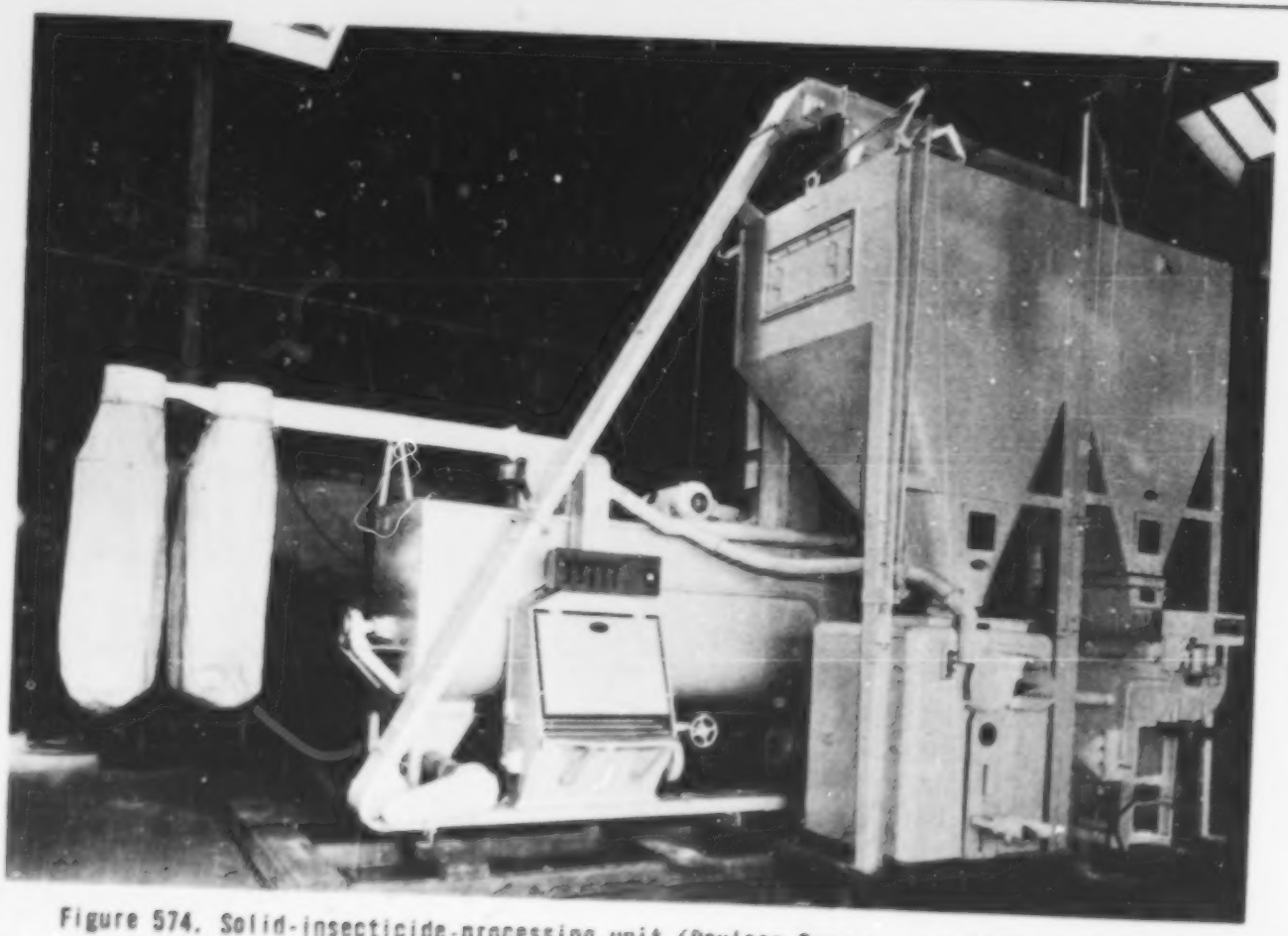


Figure 574. Solid-insecticide-processing unit (Poulsen Company, Los Angeles, Calif.).

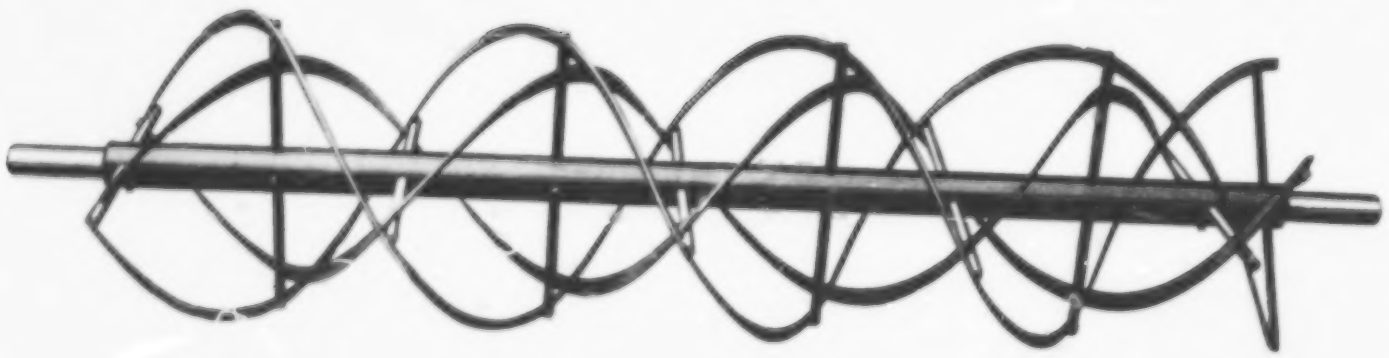


Figure 575. Ribbon blender screw (Link-Belt Company, Los Angeles, Calif.).

When the toxicant is in the solid state, the ingredients of the blend are intimately ground, usually in stages, and blended by mechanical mixing operations. The equipment employed consists of standard grinding and size reduction machines such as ball mills, hammer mills, air mills, disc mills, roller mills, and others. A specific example of a grinding and blending facility for solid insecticide is shown in Figures 576 and 577. This installation is used for compounding DDT dust. The grinding and blending operations are done in two stages. First, the material is processed in the premix grinding unit and then transferred to the final grinding and blending unit.

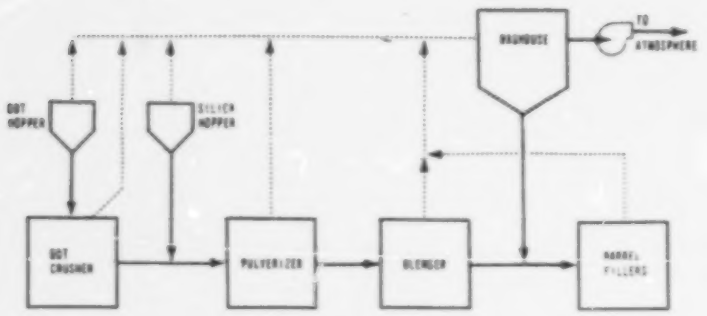


Figure 576. Premix grinding unit.

Figure 576 illustrates the equipment comprising the premix grinding unit. This unit is used for the initial grading and blending of DDT and silica mixtures. DDT flakes, 75 percent of which have a particle size of 1-centimeter diameter, are emptied from sacks into a hopper. A conveyor takes this DDT to a crusher from which it is conveyed to a pulverizer. Finely ground silica (0.2- to 2-micron size) is introduced to the pulverizer. Silica is added because DDT becomes waxy at temperatures approaching its melting point and has a tendency to cake and resist grinding. Silica acts as a stabilizing agent. The coarsely ground silica-DDT mixture is then discharged into a ribbon blender for thorough mixing before being conveyed to a barrel-filling unit, which packs the mixture for aging before its further grinding.

The final grinding unit shown in Figure 577 takes the coarsely ground DDT-silica mixture and subjects it to fine grinding and blending. The aged DDT-silica mixture is fed into a ribbon blender where additional silica and wetting agents are added to the mix. The mix is then screw conveyed to a high-speed grinding mill that uses rotating blades to shear the insecticidal mixture. A pneumatic conveying system carries the material to a cyclone separator from which it drops into another blender. After this mixing operation, the blend is finely ground by high-pressure air in an airmill. The blend is air conveyed to a reverse-jet baghouse that discharges into another blender. Additional air grinding is then repeated before the barrel filling and packing.

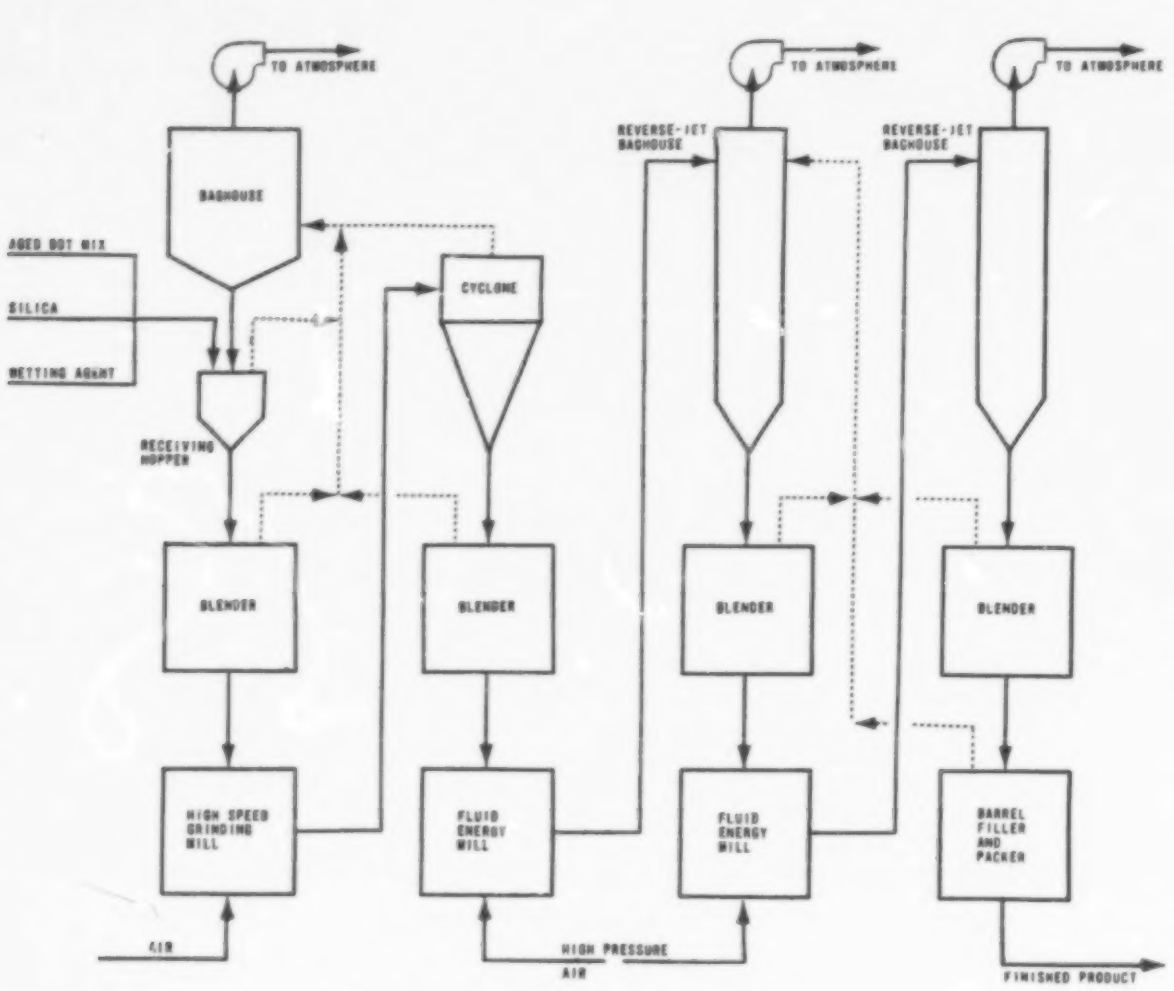


Figure 577. Final grinding and blending unit.

Liquid-Insecticide Production Methods

Liquid insecticides may be produced as either solutions, emulsions, or suspensions. The most common means of production consists of introducing a solid toxicant into a liquid carrier, which results in either a solution, emulsion, or suspension.

Figure 578 shows equipment employed in a liquid-emulsion insecticide plant that makes the emulsion by introducing a solid toxicant into a liquid carrier in the presence of an emulsifying agent. A typical formulation is:

	lb
DDT (technical)	200
Emulsifying agent No. 1	12
Emulsifying agent No. 2	12
Organic solvent	569 (79.5 gal)

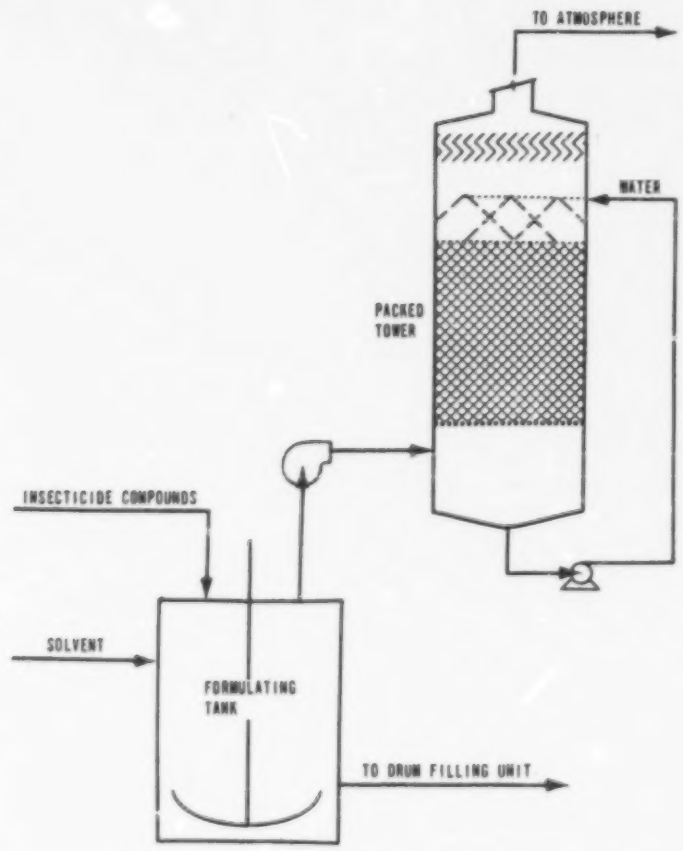


Figure 578. Liquid-insecticide-formulating unit.

The operation consists of adding the DDT to the mixing tank, the DDT being held on a horizontal wire screen located at the vertical midpoint of the tank. Organic solvent and emulsifying agents are then pumped into the mixing tank at the approximate level of the dry DDT. The mixture is continually agitated, both during and after the addition of the liquids, until the desired emulsified state is achieved. The finished product is then pumped to the drum-filling station for packaging.

THE AIR POLLUTION PROBLEM

As can be seen from the installations just described, air pollutants generated by the insecticide industry are of two types--dusts and organic solvent vapors.

To collect insecticide dusts, high-efficiency collectors are mandatory, since in many instances, the dust is extremely toxic and cannot be allowed to escape into the atmosphere, even in small amounts. The moderate fineness, 0.5 to 10 microns, of the dust necessitates using collectors that are effective in these particle size ranges. For the most part, the dusts encountered are noncorrosive.

Organic solvent vapors emitted from liquid-insecticide production processes ordinarily originate from relatively nonvolatile solvents. These vapors are of such concentration. nature, and quantity as to be inoffensive from a viewpoint of air pollution.

HOODING AND VENTILATION REQUIREMENTS

Because of the toxicity of the dusts used in the manufacture of insecticides, it is important that all sources of dust be enclosed or tightly hooded to prevent exposure of this dust to personnel in the working area. Wherever possible, the sources should be completely enclosed and ventilated to an air pollution control device. Some of the sources emitting dust are bag packers, barrel fillers, hoppers, crushers, conveyors, blenders, mixing tanks, and grinding mills. Of these, the crushing and grinding operations are the largest sources of emission. In most cases, these are not conducive to complete enclosure, and hoods must be employed. Indraft velocities through openings in hoods around crushers and mills should be 400 fpm or higher. Velocities through hood openings for the other operations, where dust is released with low velocities, should be 200 to 300 fpm.

AIR POLLUTION CONTROL EQUIPMENT

Baghouses employing cotton sateen bags are the most common means of controlling emissions from the insecticide-manufacturing industry. In some applications, water scrubbers, of both the spray chamber and the packed-tower types, are used to control dust emissions. Inertial

separators such as cyclones and mechanical centrifugal separators are not used because collection efficiencies are not high enough to prevent the smaller size toxic particles from being emitted into the atmosphere.

In the solid-insecticide-processing unit previously discussed and illustrated in Figure 574, air pollution control is achieved by dust pickup hoods located at the inlet rotary sifter and at the automatic bag packer. The dust picked up at these points is filtered by the use of cloth bags. Most units of this type are entirely enclosed, air contaminants being discharged only at the inlet to the unit and at the outlet. The contaminants emitted are extremely fine dust and, since no elevated temperatures are encountered and the materials handled are not particularly corrosive to cloth, can be easily collected by simple cloth bag filters. If extremely large throughputs are encountered, a conventional baghouse may be required. Since no extreme conditions of operation are generally involved, the most widely used filter material is a cotton sateen cloth.

In larger installations, such as those illustrated in Figures 576 and 577 for compounding DDT dust, several baghouses are usually used. In the premix grinding unit shown in Figure 576, the air pollution control equipment consists of an exhaust system discharging into a baghouse, which is equipped with a pullthrough exhaust fan. The exhaust ducting connects to both the DDT and the silica hoppers, the DDT crusher, the blender, and the barrel-filling unit. Dust collected in the baghouse is conveyed to the barrel-filling unit for packaging.

The final grinding unit, shown in Figure 577, uses air pollution control equipment consisting of a baghouse that serves the receiving hopper, the blenders, and the cyclone air discharge of the high-speed grinding mill. Dust collected in this baghouse is recycled to the feed blender. The final blenders and the barrel filler and packer are vented to one of the reverse-jet baghouses serving the fluid energy mill. As in the case of mixing liquid toxicant with dust, the material collected is not corrosive to cotton cloth, and no elevated temperatures are encountered. In this installation, cotton sateen bags of 1.12 to 1.24 pounds weight per yard with an average pore size of 0.004 inch are employed as the filtering medium.

In liquid-insecticide manufacturing, air pollution control problems usually entail collection of dusts in a wet airstream. Baghouses cannot, therefore, be used, and some type of scrubber must be employed. For the liquid-emulsion insecticide plant shown in Figure 578, the air pollution control equipment for the solid and liquid aerosols consists of a packed tower that vents the mixing tank. The tower is packed with 1-inch Intalox saddles, the packing being 4-1/2 feet high, which equals a volume of 14 cubic feet. The water rate through the tower is approximately 20 gpm. The tower is used to control dust emissions from the mixing tank, which occur when dry material is charged to the tank, and also occur during the first stages of agitation. Solvent vapors are not effectively prevented by the tower from entering the atmosphere since the solvent is insoluble in water. Solvent emissions originate from the storage tank and drum-filling unit. In the installation described, no provision is made to prevent the solvent from escaping to the atmosphere since total solvent emissions are calculated to be only 5.4 pounds per day.

HAZARDOUS RADIOACTIVE MATERIAL

Although the responsibility for overseeing the control of radioactive materials is predominantly that of the Federal government, more and more responsibility is expected to be placed at state and local levels. For this reason, those concerned with air pollution must become acquainted with the problems associated with this new field, particularly those problems arising as more and smaller industries make use of radioactive materials.

HAZARDS IN THE HANDLING OF RADIOISOTOPES

The hazards encountered in handling of radioisotopes may be classified in order of importance as follows: (1) Deposition of radioisotope in the body, (2) exposure of the whole body to gamma radiation, (3) exposure of the body to beta radiation, and (4) exposure of the hands or other limited parts to beta or gamma radiation. Deposition of a radioisotope in the body occurs by ingestion, inhalation, or absorption through either the intact or injured body surface. Inhalation of a radioactive gas, vapor, spray, or dust may occur. Spray or dust is particularly hazardous because of the large fraction of contamination retained by the lungs (National Bureau of Standards, 1949).

Types of radiation are listed in Table 232. The ranges of activity may be defined as: (1) Tracer level, less than 1×10^{-6} curie; (2) low level, 1×10^{-6} to 1×10^{-3} curie; (3) medium level, 1×10^{-3} curie to 1 curie; and (4) high level, 1 curie and over. The handling of tracer quantities of radioisotopes usually presents no external hazard. Ordinary laboratory manipulations are performed with special precautions

Table 232. TYPES OF RADIATION

Type of radiation	Physical nature	Distance of travel in air	Effective shielding	Usual means of detection
Alpha (α)	Heavy particle, helium nucleus, double positive charge	Few inches maximum	Skin or thin layer of any solid material	Proportional counter, ion chamber, scintillation counter
Beta (β)	Light-particle electron, single negative charge	Few yards maximum	One-half inch of any solid material	Geiger counter, film badge, dosimeter
Gamma (γ)	Ray, similar to X-ray	Very long	Lead, other heavy metals, concrete, tightly packed soil	Geiger counter, ion chamber, film badge, dosimeter
Neutron (η)	Moderately heavy particle, neutral charge	Very long	Water, paraffin	Proportional counter containing boric compound, ion chamber with cadmium shield

to prevent absorption of radioactive material by the body.

THE AIR POLLUTION PROBLEM

Radioactive materials used in industry are a definite hazard today and will become an increasing rather than a diminishing hazard in the future. In industry, the maximum permissible dose of direct, whole-body radiation of persons from all radioactive materials, airborne or nonairborne, is 5,000 millirem per year. There is greater likelihood that this limit will be reduced than that it will be increased. Airborne radiological hazards can result from routine or accidental venting of radioactive mists, dusts, metallurgical fumes, and gases and from spillages of liquids or solids. Presently existing governmental regulation of the rate of venting airborne, radioactive materials consists primarily of specific limitations based upon individual chemical compounds or upon concentrations of radioactivity from single vents. No concepts have been promulgated concerning methods of controlling total radioactive air pollution from all sources in an entire area. Whether it will be either desirable or necessary to find a solution or solutions to these problems is an unanswered question.

The characteristics of radioactive, gaseous or airborne, particulate wastes vary widely depending upon the nature of the operation from which they originate. In gaseous form they may range from rare gases, such as argon (A^{41}) from air-cooled reactors, to highly corrosive gases, such as hydrogen fluoride from chemical and metallurgical processes. Particulate matter or aerosols may be organic or inorganic and range in size from less than 0.05 micron to 20 microns. The smaller particles originate from metallurgical fumes caused by oxidation or vaporization. The larger particles may be acid mist droplets, which are low in specific gravity and remain suspended in air or gas streams for longer periods (Liberman, 1957).

Characteristics of Solid, Radioactive Waste

Solid, radioactive wastes are of two general classes--combustible and noncombustible. Typical combustible solid wastes are paper, clothes, filters, and wood. Noncombustible, solid wastes may include nonrecoverable scrap, evaporator bottoms, contaminated process equipment, floor sweepings, and broken glassware. If inadequate provisions are made for proper handling and disposal of these wastes, a distinct nuisance, and, under certain circumstances, even a hazard, could result.

Characteristics of Liquid, Radioactive Waste

Liquid, radioactive wastes are evolved in all nuclear energy operations-from laboratory research to full-scale production. Liquid wastes with relatively small concentrations of radioactivity originate in laboratory operations where relatively small quantities of radioactive materials are involved. Other sources are the processing of uranium ore and feed material; the normal operation of essentially all reactors, particularly water-cooled types; and the routine chemical processing of reactor fuels. High-activity liquid wastes

are produced by the chemical processing of reactor fuels.

Problems in Control of Airborne, Radioactive Waste

Removal of radioactive suspended particles, vapors, and gases from "hot" (radioactive) exhaust systems before discharge to the atmosphere is a serious problem confronting all nuclear energy and radiochemistry installations. Removal is necessary in order to prevent dangerous contamination of the immediate and neighboring areas. Air pollution brought about through discharge of radioactive stack gas wastes from ventilation systems is only partially avoided by filter devices, no matter how efficient they may be, if the discharge contains radioactive gases. In systems using filter media such as paper, cloth, glass fiber, and so forth, activity eventually builds up in the filter media through dust loading; the same situation applies to electrical precipitators.

Another problem in the control of airborne, radioactive waste is the low dust loading of exhaust streams. The dust concentration of ambient air is usually about 1 grain per 1,000 cubic feet. At installations handling radioactive material, owing to precleaning of the entering air, aerosols may have concentrations as small as 10^{-2} to 10^{-3} grain per 1,000 cubic feet. In contrast, loadings of some industrial gases may reach several hundred grains per cubic foot, though values of 20 grains or less per cubic foot are more common.

An outstanding feature to consider with air-cleaning requirements for many nuclear operations is the extremely small permissible concentrations of various radioisotopes in the atmosphere (see Table 233). Often, removal efficiencies of about 99.9 percent or greater for particles less than 1 micron in diameter are necessary. This high removal efficiency limits the selection of control equipment for radioactive applications.

HOODING AND VENTILATION REQUIREMENTS

Hooding

Hooding for radiochemical processes must prevent radioactive contaminants, such as dust and fumes, from escaping into the work area and must deliver them to suitable control devices. Radioactive sources require proper shielding to prevent the escape of radiation and are not considered in this section. The materials used for construction for hoods depend upon the type and quantities of radioactivity and the nature of the process. Stainless steel, masonite, transite, or sheet steel, surfaced with a washable or strippable paint, can be used (Ward, 1952). Where it is necessary in a process to handle material that may cause dusts or fumes to form, a completely enclosed hood should be used, equipped with a glove box or dry box. Any tools used for manipulation should not be removed from the hood.

Ventilation

The recommended airflow for toxic material across the face of a hood is 150 fpm (Manufacturing Chemists' Association, 1954). Turbulence of air entering a hood can be reduced by the addition of picture frame airfoils to the edges. Hoods should not be located where drafts will affect their operation. When more than one hood is located in a room, fan motors should be operated by a single switch. The fan should freely discharge to the atmosphere and be connected to the outlet side of any control device, the motors being located outside the air ducts to prevent their contamination. Hood and ducts should be equipped with manometers to indicate that they are operating under a negative pressure.

AIR POLLUTION CONTROL EQUIPMENT

Reduction of Radioactive, Particulate Matter at Source

Reduction at the source has been defined as the design of processes so as to minimize the initial release of particulate matter at its source. The principle is not new; it is applied, for example, in the ceramics industry where dry powders are wetted and mixed as a slurry to minimize the production of dust. But its application to radioactive aerosols is particularly worthwhile since it (1) provides a cleaner effluent, (2) reduces radiation hazards involved in the maintenance of air-cleaning equipment or those resulting from the buildup of dust activity, (3) permits the use of simpler and less expensive air-cleaning equipment, and (4) becomes a part of the process once reduction has been established. In general, preventing the formation of highly toxic aerosols is preferable to cleaning by secondary equipment.

The design or redesign of processes for reduction at the source should be based upon a study of the quantity and physical characteristics of the contaminant, and the manner in which it is released. Examples of this concept are instal-

Table 233. PROPERTIES OF RADIOISOTOPES (Benedict and Pigford, 1957)

Isotope	Half-life	Type of decay	Maximum permissible concentration in air, microcuries/ml		Isotope	Half-life	Type of decay	Maximum permissible concentration in air, microcuries/ml	
			Soluble	Insoluble				Soluble	Insoluble
H^3	12.5 yr	Beta	2×10^{-7}	4×10^{-5} Sub[a]	Sb^{122}	2.8 days	Beta	6×10^{-9}	5×10^{-9}
Be^7	52.9 days	EC[b]	2×10^{-7}	4×10^{-8}	Sb^{124}	60 days	Beta, no EC	5×10^{-9}	7×10^{-10}
C^{14}	5,568 yr	Beta	1×10^{-7}		Sb^{125}	~2.7 yr	Beta	2×10^{-8}	9×10^{-10}
F^{18}	112 min	Beta	2×10^{-7}	9×10^{-8}	Te^{127}	115 days	IT	6×10^{-8}	3×10^{-8}
Na^{24}	15 hr	Beta	4×10^{-8}	5×10^{-9}	Te^{129}	33.5 days	IT	2×10^{-7}	1×10^{-7}
P^{32}	14.3 days	Beta	2×10^{-9}	3×10^{-9}	I^{131}	8.1 days	Beta	1×10^{-10}	1×10^{-8}
S^{35}	87.1 days	Beta	9×10^{-9}	9×10^{-9}	Xe^{133}	5.3 days	Beta		3×10^{-7} Sub
Cl^{36}	4.4×10^5 yr	Beta	1×10^{-8}	8×10^{-10}	Cs^{134}	2.3 yr	Beta, no EC	1×10^{-9}	4×10^{-10}
A^{41}	109 min	Beta		4×10^{-8} Sub	Xe^{135}	9.1 hr	Beta		1×10^{-7} Sub
K^{42}	12.4 hr	Beta	7×10^{-8}	4×10^{-9}	Cs^{137}	33 yr	Beta	2×10^{-9}	5×10^{-10}
Ca^{45}	152 days	Beta	1×10^{-9}	4×10^{-9}	Ba^{140}	12.8 days	Beta	4×10^{-9}	1×10^{-9}
Sc^{46}	85 days	Beta	8×10^{-9}	8×10^{-10}	La^{140}	40 hr	Beta	5×10^{-9}	4×10^{-9}
V^{48}	16 days	Beta, EC	6×10^{-9}	2×10^{-9}	Ce^{141}	33.1 days	Beta	2×10^{-8}	5×10^{-9}
Cr^{51}	27.8 days	EC, no beta	4×10^{-7}	8×10^{-8}	Pr^{143}	13.7 days	Beta	1×10^{-8}	6×10^{-9}
Fe^{55}	2.9 yr	EC, no beta	3×10^{-8}	3×10^{-8}	Ce^{144}	282 days	Beta	3×10^{-10}	2×10^{-10}
Mn^{56}	2.6 hr	Beta	3×10^{-8}	2×10^{-8}	Pm^{147}	2.6 yr	Beta	2×10^{-9}	3×10^{-9}
Fe^{59}	45.1 days	Beta	5×10^{-9}	2×10^{-9}	Sm^{151}	73 yr	Beta	2×10^{-9}	5×10^{-9}
Ni^{59}	8×10^4 yr	EC	2×10^{-8}	3×10^{-8}	Eu^{154}	16 yr	Beta	1×10^{-10}	2×10^{-10}
Co^{60}	5.3 yr	Beta	1×10^{-8}	3×10^{-10}	Ho^{166}	>30 yr	Beta	7×10^{-9}	6×10^{-9}
Ni^{63}	85 yr	Beta	2×10^{-9}	1×10^{-8}	Tm^{170}	129 days	Beta, no EC	1×10^{-9}	1×10^{-9}
Cu^{64}	12.8 hr	EC, beta	7×10^{-8}	4×10^{-8}	Lu^{177}	6.8 days	Beta	2×10^{-8}	2×10^{-8}
Zn^{65}	250 days	EC, beta	4×10^{-9}	2×10^{-9}	Re^{183}	155 days	EC	9×10^{-8}	5×10^{-9}
Ge^{71}	11.4 days	EC, no beta	4×10^{-7}	2×10^{-7}	Ir^{190}	12.6 days	EC	4×10^{-8}	1×10^{-8}
Ga^{72}	14.3 hr	Beta	8×10^{-9}	6×10^{-9}	Ir^{192}	74.4 days	EC, beta	4×10^{-9}	9×10^{-10}
As^{76}	26.8 hr	Beta	4×10^{-9}	3×10^{-9}	Au^{198}	2.7 days	Beta, no EC	1×10^{-8}	8×10^{-9}
Br^{82}	35.9 hr	Beta, no EC	4×10^{-8}	6×10^{-9}	Au^{199}	3.1 days	Beta	4×10^{-8}	3×10^{-8}
Kr^{85}	9.4 yr	Beta		3×10^{-7} Sub	Hg^{203}	47.9 days	Beta	2×10^{-9}	4×10^{-9}
Rb^{86}	19.5 days	Beta, no EC	1×10^{-8}	2×10^{-9}	Tl^{204}	3.5 yr	Beta, EC	2×10^{-8}	9×10^{-10}
Sr^{89}	53 days	Beta	3×10^{-10}	1×10^{-9}	Po^{210}	138.3 days	Alpha, beta stable	2×10^{-11}	7×10^{-12}
Sr^{90}	19.9 yr	Beta	3×10^{-11}	2×10^{-10}	At^{211}	7.5 hr	Alpha, EC	2×10^{-10}	1×10^{-9}
Y^{90}	61 hr	Beta	4×10^{-9}	3×10^{-9}	Ac^{227}	22 yr	Alpha, beta	8×10^{-14}	9×10^{-13}
Y^{91}	61 days	Beta	1×10^{-9}	1×10^{-9}	Th^{232}	1.39×10^{10} yr	Alpha, beta stable	10^{-12}	10^{-12}
Nb^{95}	35 days	Beta	2×10^{-8}	3×10^{-9}	Pa^{233}	27.4 days	Beta	2×10^{-8}	6×10^{-9}
Tc^{96}	4.2 days	EC, no beta	2×10^{-8}	8×10^{-9}	U^{233}	1.62×10^5 yr	Alpha, beta stable	2×10^{-11}	4×10^{-12}
Mo^{99}	67 hr	Beta	3×10^{-8}	7×10^{-9}	Th^{234}	24.1 days	Beta	2×10^{-9}	10^{-9}
Pd^{103}	17 days	EC	5×10^{-8}	3×10^{-8}	U^{238}	4.49×10^9 yr	Alpha, beta stable	3×10^{-12}	5×10^{-12}
Rh^{103}	57 min	IT[c]	3×10^{-6}	2×10^{-6}	Pu^{239}	2.44×10^4 yr	Alpha, beta stable	6×10^{-14}	1×10^{-12}
Rh^{105}	36.5 hr	Beta	3×10^{-8}	2×10^{-8}	Am^{241}	470 yr	Alpha, beta stable	2×10^{-13}	4×10^{-12}
Ag^{105}	40 days	EC	2×10^{-8}	3×10^{-9}	Cm^{242}	162.5 days	Alpha, beta stable	4×10^{-12}	6×10^{-12}
Ru^{106}	1 yr	Beta	3×10^{-9}	2×10^{-10}					
Cd^{109}	470 days	EC, no beta	2×10^{-9}	3×10^{-9}					
Ag^{110}	270 days	Beta, IT no EC	7×10^{-9}	3×10^{-10}					
Ag^{111}	7.6 days	Beta	1×10^{-8}	9×10^{-9}					
Sn^{113}	112 days	EC, no beta	1×10^{-8}	2×10^{-9}					
In^{114}	49 days	IT, no EC	4×10^{-9}	7×10^{-10}					

[a] Values given are for submersion in an infinite cloud of gaseous material.
[b] Orbital-electron capture.
[c] Isomeric transition.

lation of glass fiber filters on the inlet of ventilating or cooling air to minimize the irradiation of ambient dust particles, and treatment of ducts to minimize corrosion and flaking (Friedlander et al., 1952).

Design of Suitable Air-Cleaning Equipment

The most satisfactory control of particulate contamination with air-cleaning equipment results from using combinations of the various collectors. These installations should be designed to terminate with the most efficient separator possible, the nature of the gases being considered. To reduce maintenance, less efficient cleaners capable of holding or disposing of most of the weight load should be placed before the final stage. It is good practice to arrange the equipment in order of increasing efficiency. A typical example of such an arrangement is a wet collector such as a centrifugal scrubber to cool the gases and remove most of the larger particles, an efficient dry filter such as a glass fiber filter to remove most of the remaining particulate matter, and a highly efficient paper filter to perform the

final cleaning. If the gases are moist, as in this example, the paper filter should be preceded by a preheater to dry the gases (Friedlander, 1952).

An air-cleaning installation for highly toxic aerosols should fulfill the following requirements (Friedlander et al., 1952):

1. "It should discharge innocuous air.

2. "The equipment should require only occasional replacement and should be designed for easy maintenance. Frequent replacement or cleaning entails excessive exposure to radiation and the danger of redispersing the collected material.

3. "The particulate matter should be separated in a form allowing easy disposal. The use of wet collectors, for example, poses the additional problem of disposing of volumes of contaminated liquid. Wet collection does, however, reduce considerably the danger of redispersion.

4. "Initial and maintenance costs, as well as operating costs, should be as low as possible while fulfilling the preceding three conditions. In this respect, pressure drop is generally an important consideration."

Reverse-jet baghouse

One type of commercially available dust collector that meets the requirements of filtering airborne, radioactive particles from ventilation exhaust streams is a bag filter employing what is called reverse-jet cleaning. This type of baghouse (described in Chapter 4) has an efficiency as high as the conventional cloth bag or cloth screen collector and is particularly adapted to an installation where the grain loading of the effluent is low. The bag material is a hard wool felt of the pressed type, about 1/16-inch thick, or a cloth woven of glass fibers. The gas flow is likely to be around 10 to 40 cfm per square foot of bag area when the pressure drop is maintained at usual values such as 2 to 7 inches water column (Anderson, 1958).

The conventional cloth bag or cloth screen collectors, which are cleaned periodically by automatic shaking devices, may allow a puff of dust to escape after the shaking operation. The problem of maintenance in this instance presents a contamination and radiation hazard. For this reason, the reverse-jet baghouse is generally preferred.

Wet collectors

Another method of treating contaminated exhaust air before discharge to the atmosphere involves the use of wet collectors of various types. These collectors are relatively effective on gases. Investigation covering changing of water supply or recirculating has shown the latter procedure useful for considerable periods of time without apparent adverse effect. Evaporation is compensated for by fresh supply. Insoluble radioactive salts, soluble salts, and other radioactive particles that may form a solution, suspension, or sludge in the reservoir result in fairly high radioactivity of the scrubbing media. Precautions must be taken during maintenance to avoid carryover of the scrubbing media since the radioactive contamination of entrained liquid would be transferred to the preheater or filter, resulting in high radiation levels at those points.

Disadvantages of wet collectors

Some important disadvantages of wet collectors make them less attractive than other types of collectors. Wet collectors present the difficult problem of separating the radioactive, solid material from the water in which it is suspended. Maintenance and corrosion are serious problems. Considerable quantities of water are required, and, if the radioactive solids are not separated from the water, this in turn leads to a final storage and disposal problem.

Electrical precipitators

Radioactive, airborne particles, when given an electrical charge, can be collected on grounded surfaces. The fact that the particles are radioactive has very little to do with their behavior in an electrical precipitator. Experiments conducted with precipitators using the alpha emitter polonium and the beta emitter sulfur 35 indicate that neither material behaves in a way different from nonradioactive material.

Water-flushed-type, single-stage, industrial precipitators, and air-conditioning-type, two-stage precipitators are used for separating radioactive dusts and fumes from gases at atomic energy plants and laboratories. A small electrical precipitator of the water-flushed type with a design capacity of 200 cfm was installed to test efficiency of collecting and removing particulate radioactivity from the offgas system of an isotope recovery operation. This precipitator consists of 23 vertical collecting pipes with an ionizing wire centered in each pipe. The inside surfaces of the pipes serve as collecting

walls. For wet operation, the collecting walls are water flushed by means of spray nozzles installed at the top of each pipe. This water is recycled continuously at a rate of 35 gpm over the collecting walls while high voltage is applied to the electrodes. This unit reportedly collects more than 99.99 percent of the particulate radioactivity in the offgas at 50 to 55 kilovolts when the concentration of radioactivity as solids is greater than 5.0×10^{-4} microcuries per cubic centimeter of offgas (Anderson, 1958).

Based upon tests made at the Oak Ridge National Laboratory, Anderson (1958) makes the following evaluation of precipitators used in radioactive applications:

1. "Electrical precipitators are not intended to collect the ultra fine particles which may be discharged from radiochemistry installations.

2. "With uneven airflow, the air velocity through some of the collector cells may be sufficiently above velocity limits to blow off collected wastes which would then be discharged to the atmosphere.

3. "Efficient operation depends a great deal on the regularity with which the unit is cleaned. At best the electrical precipitator is only approximately 90 percent efficient. This may be demonstrated by the fact that dense clouds of tobacco smoke fed into the precipitator will escape from it in concentrations great enough so that the escaping smoke can be seen. The blue color of tobacco smoke is evidence that most of its particles have a diameter less than the wavelength of light, which is roughly 0.5 micron.

4. "For absolute efficiency an after-filter of the Cambridge or MSA Ultra-Aire type is necessary to catch the dirt should the precipitator short circuit.

5. "Difficulty may be experienced if the dust-load builds up faster than it can be removed eventually becoming so heavy that arcing occurs between the dirt bridges resulting in a fire hazard.

6. "Devices such as the single-stage industrial precipitator and the air-conditioning type two-stage precipitator accomplish only one phase of the problem. The final disposal of radioactive wastes collected and accumulated during operation and maintenance still remains."

Glass fiber filters

Glass fiber or glass fiber paper is often used as a filter medium and is effective in the operation of radiochemistry hoods, canopies, and gloved boxes. One of the most efficient lightweight, inorganic filters developed to date is made with a continuous, pleated sheet of microglass fiber paper. The pleats of the glass paper are separated by a corrugated material (paper, glass paper, aluminum foil, plastic, or asbestos paper) for easy passage of air to the deep pleats of the filter paper. The assembly of the filter paper and corrugated separators is sealed in a frame of wood, cadmium plated steel, stainless steel, or aluminum. This construction permits a large area of filter paper to be presented to the airstream of a correspondingly low resistance (Flanders Filters, Inc., Riverhead, N.Y.).

Glass fiber, from which filters are made, withstands temperatures up to 1,000°F. It is noncombustible and has extremely low thermal conductivity and low heat capacity. The fibers are noncellular, are like minute rods of glass, and do not absorb moisture; however, water can enter the interstices. The material is relatively nonsettling, noncorrosive, and durable. It is resistant to acid fumes and vapors, except hydrogen fluoride.

The installation and replacement costs of glass fiber filters are low. Final disposal of used filters may be accomplished by incinerating at over 1,000°F with provisions for decontaminating the stack gases. This melts the glass fibers, reducing the physical mass to the size of a glass bead. Thus, glass fiber filters provide, in part, a very good answer to the problem of control and final disposal of radioactive contaminants.

Paper filters

A highly efficient paper filter medium can be used with adequate effectiveness on incoming ventilating air and as a final cleaner in many instances. This type filter is composed of asbestos cellulose paper. A more recently developed filter has a glass fiber web. It is designed and manufactured in corrugated form to increase the available filter area and loading capacity and to reduce initial resistance. The filter units are tested at rated capacity with standard U.S. Army Chemical Corps test equipment for resistance and initial penetration and are unconditionally guaranteed to be at least 99.95 percent effective against 0.3-micron-diameter dioctyl phthalate particles. This filter performs as well as, or better

than, the earlier paper types and under temperatures up to 1,000°F.

Airborne, radioactive wastes are only part of the control and disposal problem of nuclear energy and radiochemistry installations. Solid and liquid, radioactive wastes are subject to the same limitations on disposal to the environment.

The methods of disposing of the final waste from the collection systems present additional problems, as follows (Anderson, 1958):

1. "Incineration results in stack gas and particle discharge which is a cycle of the entire problem repeated over again.

2. "Direct burial results in redispersal and ground contamination with associated problems related to the ground water table.

3. "High dust or particle loading capacity results in high radioactivity of the collecting media.

4. "Vapors, acid fumes and unfilterable gases may cause rapid deterioration and disintegration of filter media resulting in a maintenance and health hazard problem.

5. "Mechanical replacement costs are high because of the remote handling involved.

6. "An auxiliary unit for emergency or maintenance shutdown must be available to prevent the possibility of reverse flow of the air stream out of "hot" equipment into controlled rooms and areas."

Disposal and Control of Solid, Radioactive Waste

The most common method of disposal of solid, radioactive wastes is land burial at isolated and controlled areas. The earth cover over these burial pits is usually about 12 feet, and the surface is monitored regularly. A method used for disposal of low-level, radioactive, solid wastes consists of putting the wastes in concrete and dumping it at sea. Incineration of combustible, solid wastes is practiced, with provisions for decontaminating the flue gases (Shamos and Roth, 1950).

Disposal and Control of Liquid, Radioactive Waste

Low-level, radioactive, liquid wastes, under proper environmental conditions, are susceptible to either direct disposal to nature or disposal after minimum treatment. Treatment processes used include coprecipitation, ion exchange, biological systems similar to sewage treatment methods, and others. Only to the extent that it is absolutely safe, maximum use is made of the dilution factors that may be available in the environment and that can be assessed quantitatively.

High-activity, liquid wastes associated with the chemical processing of reactor fuels constitute the bulk of the engineering problem of disposal of radioactive wastes. Highly radioactive, liquid wastes are currently stored in specially designed tanks. Since the effective life of the fission products constituting the wastes may be measured in terms of hundreds of years, tank storage is not a permanent solution to the disposal problem. Evaporation before storage is generally practiced to reduce storage volume and cost. The degree to which evaporation is carried out is limited in some instances by the percentage of solids present in the waste or by considerations of corrosion.

There are several practical approaches to ultimate, safe disposal of high-activity, liquid wastes. The actual fission products in radioactive waste material may be fixed in an inert, solid carrier so that the possibility of migration of the radioactivity into the environment is eliminated or reduced to acceptable and safe limits. The carrier containing the radioactive material could then be permanently stored or buried in selected locations. Fixation on clay, incorporation in feldspars, conversion to oxide, elutriation of the oxide, and fixation of the elutriant are examples of systems under development.

Because of the particular radiotoxicity and long half-life of strontium-90 and cesium-137, the removal and separate fixation and handling of these two isotopes would substantially reduce the effective life and activity of the waste and facilitate its final disposal. With cesium and strontium removed, the possibilities of safe disposal into the environment under controlled conditions are greatly increased.

It may be practical to dispose of the wastes underground in some cases without any treatment, into formations such as (1) spaces prepared by dissolution in salt beds or salt domes, (2) deep basins containing connate brines and with no hydraulic or hydrologic connection to potable waters or other potentially valuable natural resources, and (3) special excavations in selected shale formations (Liberman, 1957).

OIL AND SOLVENT RE-REFINING

Many millions of gallons of oils and solvents are used annually for lubricating vehicle engines and other machinery, transmitting pressure hydraulically, cleaning manufactured articles and textiles, and dissolving or extracting soluble materials. In the course of their usage, these oils and solvents accumulate impurities, decompose, and lose effectiveness. The impurities include dirt, scale, water, acids, decomposition products, and other foreign materials. Reclaiming some of these oils and solvents for reuse by removal of the impurities can be effected in many instances by re-refining processes.

Most re-refiners must practice stringent economies to survive, and for this reason, secondhand, cannibalized, or makeshift equipment is often employed. Many re-refiners also neglect maintenance, repairs, and general housekeeping in order to keep operating costs low. As a result, air pollution control is minimal or lacking unless made mandatory by legislation.

RE-REFINING PROCESS FOR OILS

Lubricating oils collected from service stations are the main source of supply. A typical scheme for re-refining lubricating oil is shown in Figure 579. Re-refining is normally a batch process. Treating clay, for example, Fuller's earth, is added to the contaminated oil at ambient temperature to aid in the removal of carbon materials. The mixture is next circulated through a fired heater, usually a pipe or tube still, to a flash tower for removal of diluent hydrocarbons and water. The oil being reclaimed and the products desired determine the final temperature (300° to 600°F). Live steam, introduced at the base of the flash tower, is used to assist in this phase of the operation. Besides distilling off the light fractions contained in the oil, the steam prevents excessive cracking of the oil at the higher temperatures.

A barometric condenser maintains a vacuum on the tower. The overhead vapors containing steam, low-boiling organic materials, and entrained hydrocarbons are aspirated through the condenser to a separator tank. The condensate, consisting of light gas, oil, and water, is collected and separated in the separator tank. Noncondensible gases are usually incinerated in fireboxes of adjacent combustion equipment. The light oil condensate is decanted from the water and is suitable as liquid fuel. The contaminated water is piped to a skimming pond where it is cooled and either reused or disposed of by draining to a sewer. The oil-clay mixture is withdrawn from the tower and filtered. The oil is

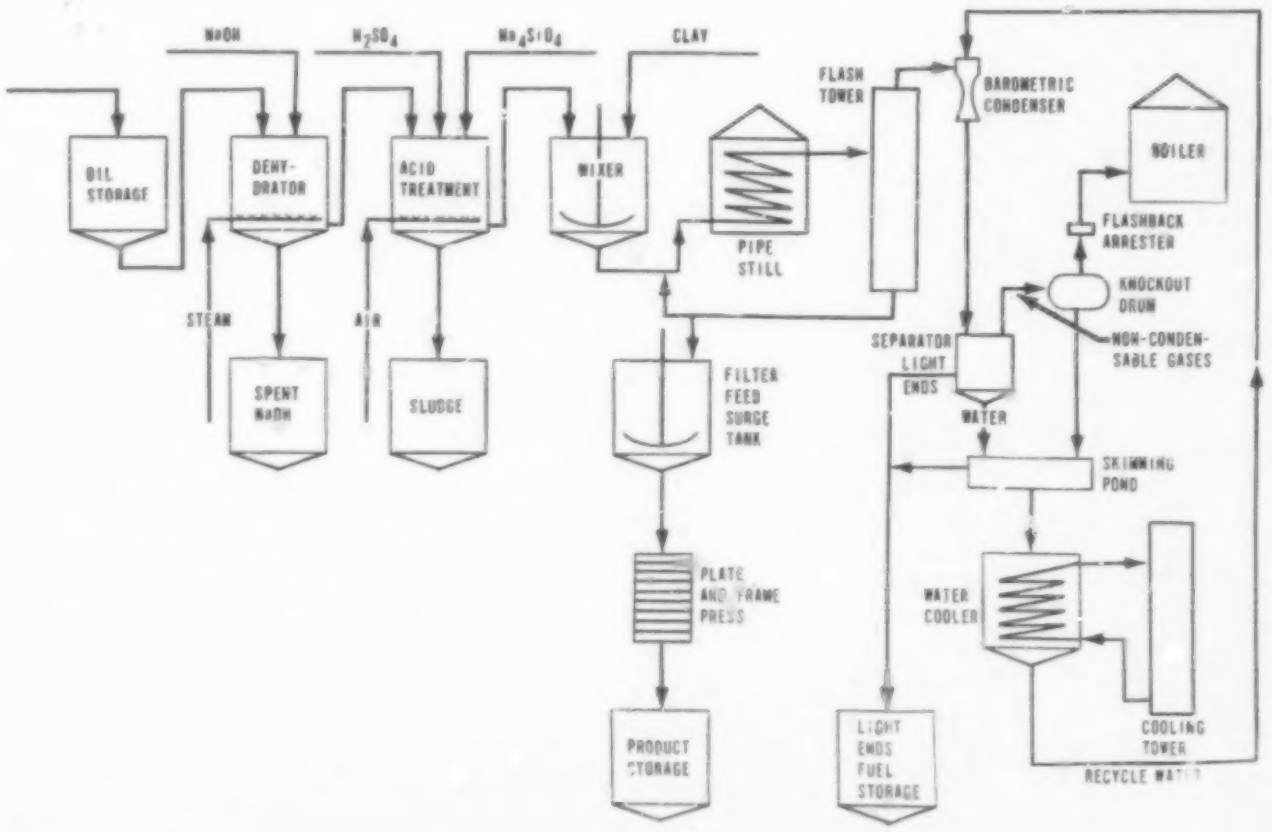


Figure 579. Composite flow sheet for re-refining process.

blended with additives and is canned or drummed. The clay is usually hauled to a dump.

In some re-refineries, the process is preceded by a dehydration operation. Water is removed from the oil by using sodium silicate, sodium hydroxide, and heat. Dehydrated oil is decanted from the mixture and charged to the still. Sulfuric acid treatment is also employed at some re-refineries before the refining process. The acid-treated oil is settled, decanted from the acid sludge, and neutralized with caustic. Before the clay is added, sulfuric acid treatment or air blowing may also be used to improve color of the re-refined oil.

RE-REFINING PROCESS FOR ORGANIC SOLVENTS

The typical organic solvent re-refining process is similar to that described for oil re-refining. The prime difference between the processes is that the volatilities of the organic solvents re-refined are much greater than those of lubricating oils. Mineral spirits, benzene, toluene, xylene, ketones, esters, alcohols, trichloroethylene, and tetrachloroethylene from paint, lacquer, degreasers, and dry cleaners are examples of solvents reclaimed by re-refining.

Figure 580 illustrates a typical solvent recovery system. The mixture to be processed is introduced into a settling tank to permit the solids to settle out. The supernatant liquid is then preheated and charged to a pot still topped by a fractionating section, which may be under vacuum. Vapors from the still are condensed in a water-cooled surface condenser. Refluxing may or may not be done, depending upon the product, the degree of purity desired, and the contaminants present. The condensate is accumulated in a holding tank, where a salt such as sodium carbonate is added to "break" the water from the solvent. After the water settles out, it is removed, and the solvent is drummed off as product.

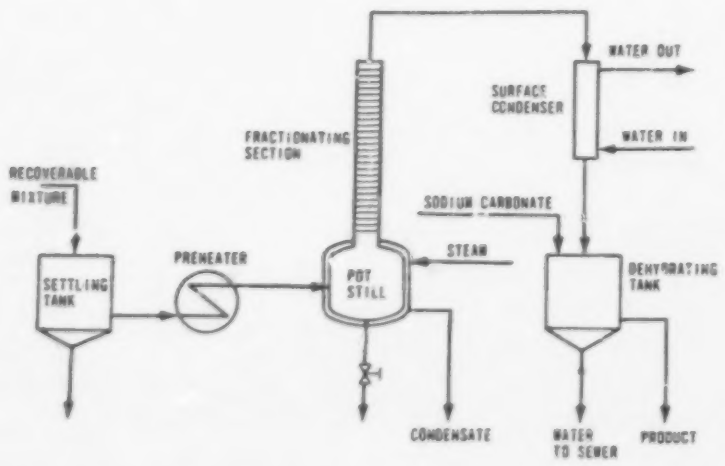


Figure 580. Typical solvent re-refining installation.

THE AIR POLLUTION PROBLEM

Air Pollution From Oil Re-refining

The two primary air pollution problems connected with oil re-refining are odors and hydrocarbon vapors.

Chief odor sources are the contaminated water and the noncondensible gases from the separator tank and dehydration tank. Obnoxious odors emanate from the skimming pond. Odors also occur from the barometric condenser leg. If the process water is aerated in a cooling tower or spray pond, a serious odor problem occurs. Other odors can originate from the dehydration operation and from sulfuric acid sludges and clay filter cakes.

In addition to air pollution from odors, oil re-refining processes can emit some hydrocarbons into the atmosphere. These originate from the noncondensible gases and the layers of light, volatile hydrocarbons on the surface of the separator tank and the skimming pond.

Air Pollution From Solvent Re-refining

As in oil re-refining, the chief air pollution problems are odors but these are less severe than those occurring from re-refining of lubricating oil. Sources of emissions are the settling tanks during filling and sludge drawoff, the drawoff of bottoms from the still, the product receivers, and the water jet reservoir (if vacuum is produced by a barometric water jet). By creating a vacuum, the water jet entraps the solvent vapors from the still.

AIR POLLUTION CONTROL EQUIPMENT

Oil Re-refining

The most acceptable method of controlling emissions from re-refining is incineration. Usually the firebox of a boiler or heater provides adequate incineration. The separator tank must be covered and vented to a firebox. The vent line should be equipped with a knockout drum and a flashback arrester. Additional safety protection can be achieved by introducing live steam into the vent line upstream from the firebox. Other vessels, for example, dehydrating tanks and mixing tanks, may be tied into this system. Emissions from the barometric, or contact,

condenser can be controlled by maintaining a closed recycle water system or by modifying the operation by substituting a shell-and-tube-type condenser.

Recycle water, highly odorous from contact with the oil and heated by contact with the hot vapors, must be allowed to cool before reuse. It can be controlled by cooling in a covered settling tank that is properly vented to an operating boiler or heater firebox. Contaminated recycle water must not be cooled by aerating in a spray pond or cooling tower.

Solvent Re-refining

Usually, in the solvent re-refining industry, air pollution control is lacking without enforcement, and solvent vapors are allowed to escape into the atmosphere. If, however, control is required, it can easily be accomplished by venting the barometric water jet vacuum system to a boiler firebox, provided appropriate flashback prevention measures have been taken. Emissions from the bottom drawoff of the still are slight since most of the volatiles have been flashed off. Emissions from the settling tank and the product receivers are normally too small to create any problems, but they can be controlled by being vented also to a boiler firebox.

CHEMICAL MILLING

The chemical milling process was developed by the aircraft industry as a solution to the problem of making lightweight parts of intricate shapes for missiles. These parts could not be formed if mechanically milled first, and no machines were available that could mill them after they were formed. Chemical milling is based upon the theory that an appropriate etch solution dissolves equal quantities of metal per given time from either flat or curved surfaces. The process was quickly adopted by the aircraft industry, and etchants were developed for chemically milling many metals used in aircraft and missiles, including aluminum, titanium, stainless steel, and magnesium.

DESCRIPTION OF THE PROCESS

Before an article can be chemically milled, the surface of the metal must be clean. The usual metal surface preparation includes (1) degreasing, (2) alkaline cleaning, (3) pickling, and (4) surface passivation. The cleaning is needed to provide a clean surface in order to insure uniform dissolving of the metal when it is submerged in the milling solution. The passivation is needed to protect the surface from oxidation in air and provide a surface that will accept and hold a masking agent or material.

Maskings are either tapes with pressure-sensitive adhesives or paint-like substances that are applied by brushing, dipping, spraying, or flow-coating. Figure 581 shows a sheet of stainless steel being flow-coated with a rubber base masking material. These paint-like maskings must be cured, usually in a bake oven. After curing, the masking is removed or stripped from those areas to be milled. Figure 582 shows one method of scribing the masking by use of a template.

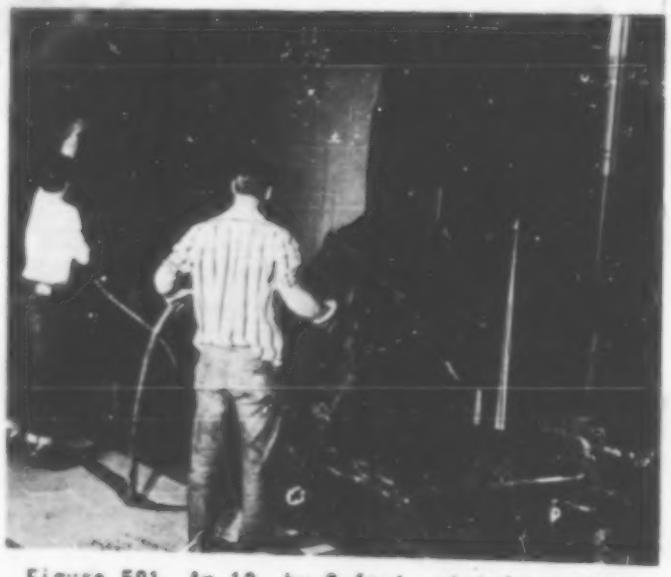


Figure 581. An 18- by 6-foot, stainless steel sheet being masked by flow-coating with a rubber-based masking (U.S. Chemical Milling Corp., Manhatten Beach, Calif.).

Milling is accomplished by submerging the prepared article in an appropriate etching solution. The depth of the cut is controlled by the length of time the article is held in the etching solution. To stop the milling action, remove the article from the etchant and rinse off the adhering solution with water. During the milling step, some metals are discolored by their etching solutions. The smutty discoloration is removed in a brightening solution such as cold, dilute nitric acid. A flow diagram of the process is shown in Figure 583.

After the milling, the paint-like masking is softened in a solution consisting, for example, of 80 percent chlorinated hydrocarbons and 20 percent high-boiling alcohols, and is then stripped off by hand. Figure 584 shows the inspection of a part. The metal thickness is measured before the masking is removed. Figure 585 shows the masking being removed from a

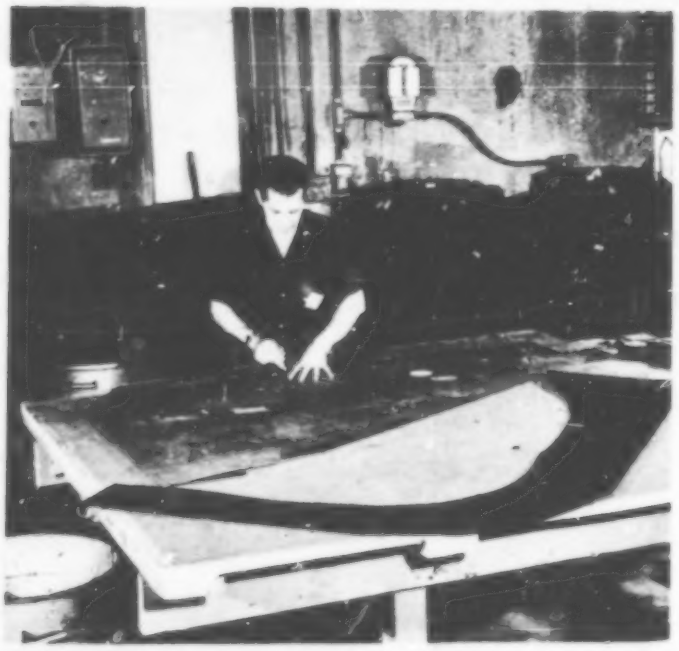
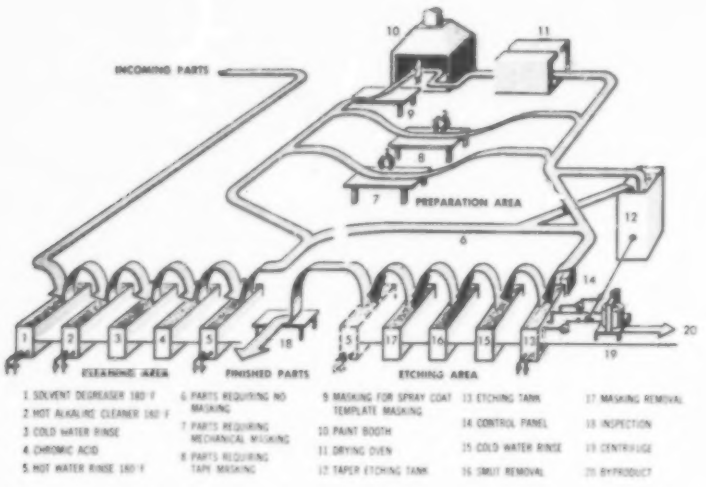


Figure 582. The masking on a titanium part is being scribed by use of a template. After scribing, the masking will be stripped from those areas shown by the holes in the templates. The stripped areas will then be milled. The black part in the foreground and those in the background have not yet been scribed (U.S. Chemical Milling Corporation, Manhatten Beach, Calif.).



This process is patented and licensed by Turco Products Co., Wilmington, Calif.

Figure 583. A flow diagram showing the typical steps necessary to the chem-milling process (Scheer, 1956).

section of a wing skin. The entire side shown was masked, and some areas of the other side were etched. In Figure 586, the masking is being stripped from a milled part.

ETCHANT SOLUTIONS

Etchants range from sodium hydroxide solution for aluminum to aqua regia for stainless steel. For milling a specific metal, the concentration of the chemical in the solution may vary widely between different operators; however, each operator controls the concentration of his solution to within very close limits. The concentration of the solution affects the milling rate, therefore, it must be closely controlled to obtain the desired rate. For milling aluminum, the solutions in use contain from 7 to 30 percent sodium hydroxide. For milling magnesium, dilute sulfuric acid solutions are adequate. Stainless steels require strong solutions, usually aqua regia fortified with sulfuric acid. In most of the milling solutions, surface-active agents are used to ensure smooth, even cuts. The surface-active agents also reduce the tendency toward mist formation by reducing the surface tension of the solution. The solutions, during milling operations, are generally maintained at constant temperatures ranging from 105°F to 190°F.

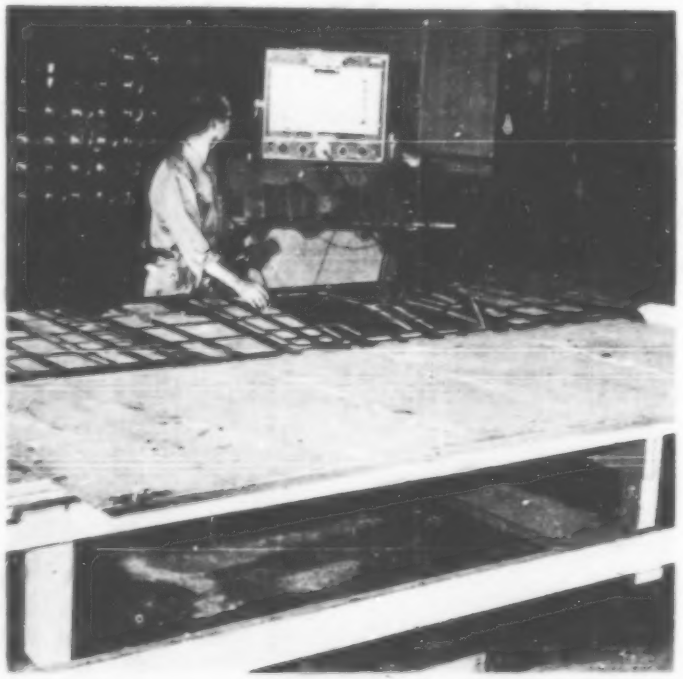


Figure 584. Inspection of milled parts. The instrument measures the metal thickness before the masking is removed (U.S. Chemical Milling Corporation, Manhatten Beach, Calif.).

THE AIR POLLUTION PROBLEM

The air contaminants emitted in the preparation of metals by chemical milling consist of mists, vapors, gases, and organic solvents.

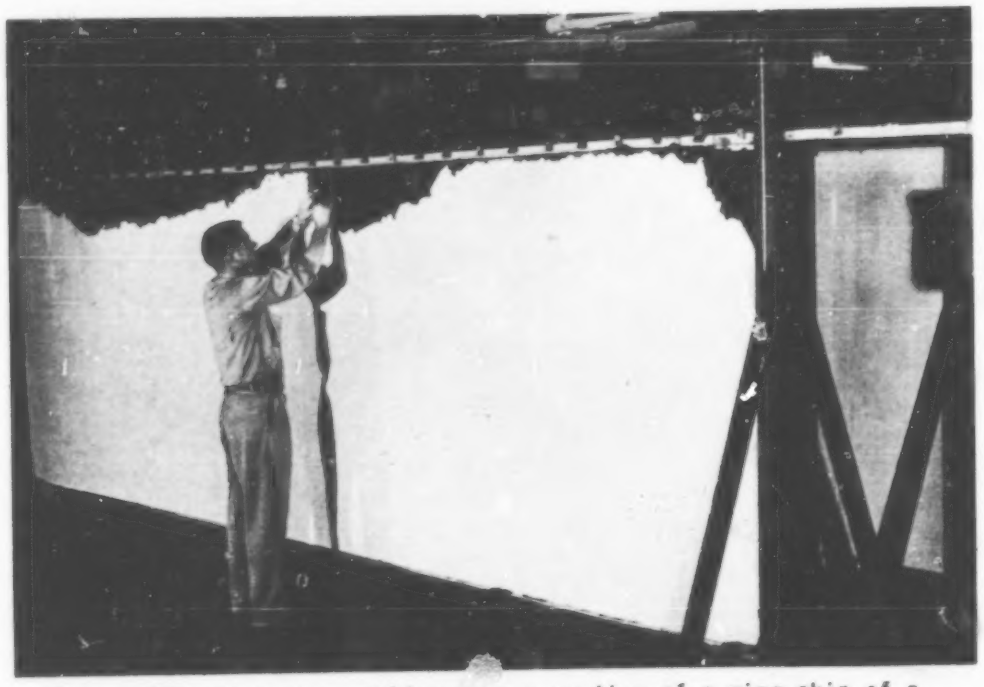


Figure 585. Stripping masking from a section of a wing skin of a B-58. The entire side shown was masked. Some areas of the other side were milled (U.S. Chemical Milling Corporation, Manhatten Beach, Calif.).

Figure 586. Masking being stripped, milled parts with masking still in place, and milled parts with masking removed (U.S. Chemical Milling Corporation, Manhatten Beacn, Calif.).

Mists

A mist of the etching solution used in a milling process is discharged from the milling tank owing to entrainment of droplets of the solution by the gas bubbles formed by the chemical action of the etchant on the metal. The amount of mist generated depends upon factors such as the nature of the chemical reaction, the solution temperature, and the surface tension of the solution. Since the solutions from which the mists are formed are very corrosive, the mists, too, are very corrosive and are capable of causing annoyance, or a nuisance, or a health hazard to persons, or damage to property.

Vapors

Some of the acid solutions used, such as hydrochloric and nitric, have high vapor pressures at the temperatures used for the milling process; therefore, appreciable amounts of acid vapors are discharged. Unlike the discharge of mists, which occurs only during the milling, the vapors are discharged continuously from the hot solution. Under certain atmospheric conditions, the vapors condense, forming acid mists in the atmosphere.

Gases

Since hydrogen is formed in chemical milling, proper ventilation must be provided to prevent the accumulation of dangerous concentrations of this gas.

Solvents

Organic solvent vapors may be emitted from the vapor degreaser, the maskant area, and the curing station in the cleaning and masking processes. This type of air contaminant, and the method of controlling it are described elsewhere in this manual. Alkaline cleaning, pickling, and passivating tanks from the other phases of the cleaning processes have been found to be minor sources of air pollution.

HOODING AND VENTILATION REQUIREMENTS

The air contaminants released from chemical milling tanks can be captured by local exhaust systems. Since open tanks are used to provide unobstructed working area, most exhaust systems employ slotted hoods to capture the mists and vapors. In designing slot hoods for chemical milling equipment, it is particularly important to provide for the elimination of excessive cross-drafts as well as for adequate distribution of ventilation along the entire length of the hoods. The minimum ventilation rates previously mentioned in Chapter 3 are for tanks located in an area having no cross-drafts. If the tank is to be located outside or in a very drafty building, either the ventilation rate will have to be greatly increased or baffles must be used to shield the tank from winds or drafts. In some instances, both baffles and increased ventilation are needed.

Adequate distribution of ventilation along the entire length of a slot can be attained by providing a high slot velocity and a relatively low plenum velocity. The slot velocity should be at least 2,000 fpm, and the plenum velocity should be not more than half of the slot velocity. With hoods more than 10 feet in length, either multiple takeoffs or splitter vanes are needed. Enough takeoffs or splitters should be used to reduce the length of the slot to sections not more than 10 feet long.

Under excessively drafty conditions, a hood enclosing the tank can be used to advantage. The hood should cover the entire tank and have sufficient height to accommodate the largest metal sections that can be handled in the tank. Various methods have been used to get work into and out of the tank. In one installation, the hood has doors on one end, and a monorail, suspended below the hood roof, that runs out through the doors. The work is carried on the monorail into the hood and above the solution. After the work is lowered into the solution, the doors are closed, when necessary, to ensure complete capture of the air contaminants created. In another installation, the hood is left open on one end, and a slot hood placed across the opening. The top of the hood is slotted to provide for the movement of the crane cable. This slot is nominally closed with rubber strips, which are pushed aside by the cable during movement of the crane.

AIR POLLUTION CONTROL EQUIPMENT

Many types of wet collectors that can control the emissions from chemical milling tanks are commercially available. The one most commonly used is the spray and baffle type, owing probably to its low cost and ease of coating with corrosion-inhibiting materials. Moreover, the operation and maintenance of this type are simple and inexpensive compared with those of other types of scrubbers.

Figure 587 shows an exhaust and mist control system employing two scrubbers, one for each side of a 24-foot-long by 6-foot-wide tank used for chemically milling stainless steel and titanium. The etching solution is a mixture of hydrochloric, nitric, and sulfuric acids and is heated to 150°F. Acid vapors discharged from the solution are captured by slot hoods, one on each side of the tank. The ducts from each hood exit downward from the center. Each hood has four splitter vanes, which divide it into four sections. The overall hood length is 24 feet, the end-sections and those adjacent being 4 feet long each, and the center section being 8 feet long. Distribution of ventilation is excellent. Each hood is supplied with 18,000 cfm ventilation, and the slot is sized to give an intake velocity of 2,000 fpm. The plenum velocity is less than 1,000 fpm. It is estimated that this system provides sufficient ventilation to capture

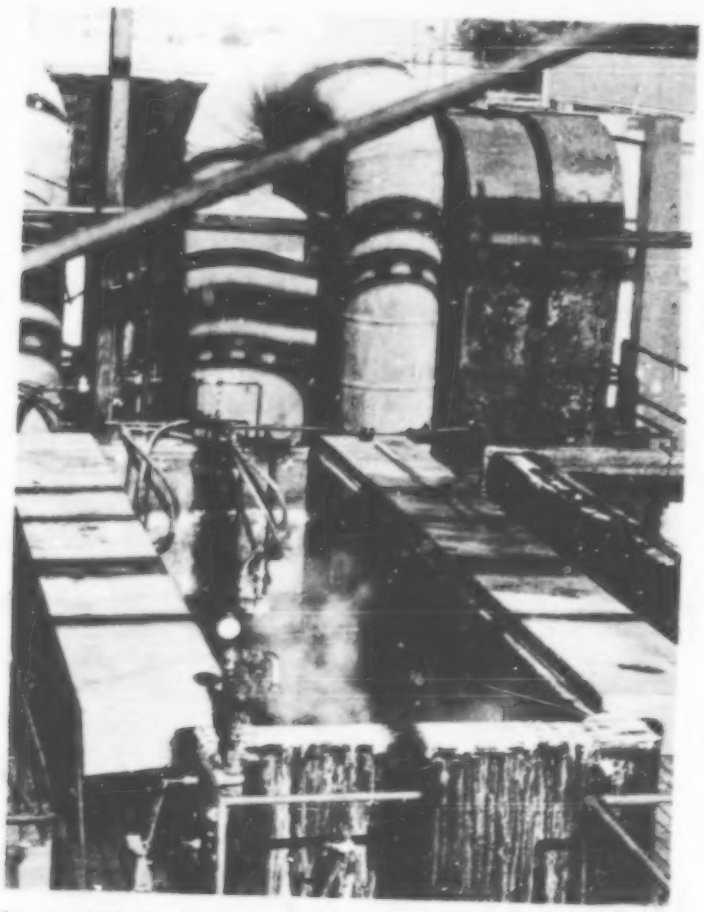


Figure 587. A tank used for the chemical milling of stainless steel, and part of its air pollution control system. The hoods, ductwork, and scrubbers shown are made entirely of polyester resin reinforced with fiberglas. The fans and discharge ducts, not shown, are steel-coated with polyester resin. (U.S. Chemical Milling Corporation, Manhatten Beach, Calif.).

at least 95 percent of the vapors emerging from the process.

The scrubbers are of the spray and baffle type, as shown in Figure 588. They are cylindrical, two baffles forming three concentric chambers. Gases enter at the top and flow down through the center cylindrical section. Water from a bank of sprays scrubs the gases as they enter this section. The bottom of the scrubber is filled with water to a depth of 1 foot. The gases and scrubbing water flow downward through the center section and impinge on the water. The gases turn 180 degrees and flow upward through the second chamber. Most of the scrubbing water remains in the sump. The depth of water in the sump is maintained at a uniform level with a float valve and an overflow line. The scrubber is equipped with a pump to circulate the sump water to the sprays. In this installation, however, only fresh water is used, the sump being kept full and overflowing all the time.

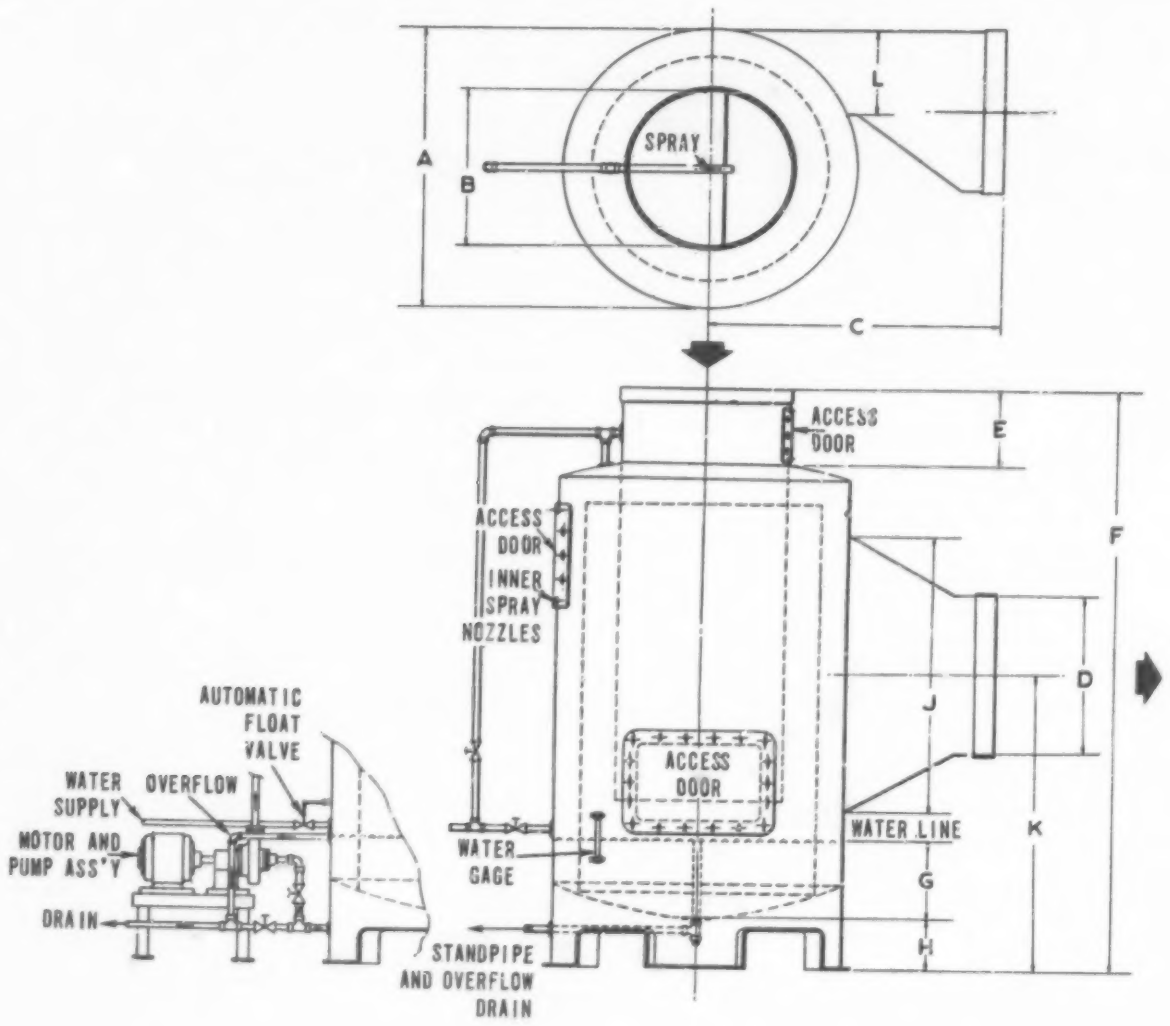
The gases flow upward through the second section and over the second baffle. They turn 180 degrees to enter the third section. In the third section, the gases flow down and around to the outlet port. Most of the entrained moisture entering the second section is removed either by impingement on the walls of that section or by centrifugal impingement during the 180-degree change of direction into the third section. The last of the entrained water is deposited on the walls of the third section. The gases then flow from the scrubber to the fan, from which they are discharged to the atmosphere through ducts.

The hoods, the scrubber, and the ductwork connecting the hoods to the scrubbers and the scrubbers to the fans are made entirely of polyester resin reinforced with glass fibers. The fans and discharge ducts are made of steel coated with polyester resin.

The existing system provides satisfactory control of the vapors. It captures an estimated 95 percent of the vapors at the tank, and the gases discharged have only a slight acid odor.

Corrosion Problems

Whenever moisture is present in an exhaust system, the iron or steel surfaces should be coated to prevent corrosion. Since, however, zinc is soluble in both acid and alkaline solutions, galvanized iron cannot be used when chemical milling tanks are vented. A coating such as polyvinylchloride (PVC), which is not attacked by either dilute acids or dilute alkalies, should be used. It has been found, however, that the PVC linings in ducts and scrubbers cannot withstand the strongly oxidizing acids used for stainless steel and titanium milling. These highly corrosive acids have been successfully handled in exhaust systems made of polyester resins reinforced with fiberglas. Hoods, ducts, and scrubbers are available made entirely of polyester-fiberglas material. Figure 587 shows an air pollution control system venting a 24-foot-long tank for stainless steel chemical milling. The hoods, ductwork up to the blowers, and the scrubbers are made entirely of polyester-fiberglas material. The steel blowers and discharge ducts are coated with polyester resin. Some blower manufacturers are now advertising blowers with scrolls made entirely of polyester-fiberglas and with steel wheels coated with the same material.



Model	Motor[a] hp	Pump gpm	Drain weight[b]	A	B	C	D	E	F	G	H	J	K	L	Spray nozzles	Drain size, in.	Min.-range-max.			
																	fpm	cfm	fpm	cfm
24	1	14	110	24	12	22	12	12½	69½	9	9	22½	35½	6	7	1	1,000	800	3,000	2,300
30	1	14	260	30	18	32½	18	12	80	10½	9	38	40	9	7	1	1,000	1,700	3,000	5,200
42	1½	18	330	42	24	43	24	12	92	12	8	42	46	12	9	1	1,000	3,000	3,000	9,000
60	1½	20	600	60	32	51½	32	12	102	14	12	50	55	18	10	1	1,000	5,200	3,000	16,000
72	2	22	963	72	42	64½	42	12	132	24	18	60	76½	24	11	1	1,000	9,500	3,000	28,000

[a]Motor is 440/220 volts, 3 phase, 60 cycle. Exhaust fan and motor furnished upon request.
[b]Does not include recirculating motor and pump.

Figure 588. A scrubber used to control the acid vapors discharged from a tank used to mill stainless steel (Lin-O-Coat scrubber, manufactured by Diversified Plastics, Inc., Paramount, Calif.).

REFERENCES

Adams, R.L. 1964.
Application of Baghouses to Electric Furnace Fume Control. JAPCA. 14(8):299-302 (Aug).

Air Moving and Conditioning Assn., Inc. 1963.
Bulletin 210. 205 W. Touhy Ave., Park Ridge, Ill.

Air Pollution Handbook.
See Magill et al.

Alden, J.L. 1948.
Design of Industrial Exhaust Systems. The Industrial Press, New York, N.Y.

Alexander, W.H., and R.L. Bradley. 1958.
Can You Justify a CO Boiler? Petrol. Refiner. 37:107-12 (Aug).

Allen, G.L., F.H. Viets, and L.C. McCabe. 1952.
Control of Metallurgical and Mineral Dusts and Fumes in Los Angeles County, California. Bureau of Mines Information Circular 7627, U.S. Department of Interior, Washington, D.C. (Apr).

American Air Filter Company, Inc. 1958.
American Filter Handbook. Louisville, Ky. 40208.

American Air Filter Company, Inc. 1964.
Calendar-Memo-Handbook. Louisville, Ky. 40208.

American Conference of Governmental Industrial Hygienists. 1960.
Threshold Limit Values for 1960. Arch. Environ. Health. 1:140-44 (Aug).

American Foundrymen's Association. 1949.
Handbook of Cupola Operation. American Foundrymen's Association, Chicago, Ill. (Des Plaines, Ill.)

American Gas Association Laboratories. 1940.
Research in Fundamentals of Atmospheric Gas Burner Design. Research Bulletin No. 10. Cleveland, Ohio (Mar).

American Petroleum Institute. 1960.
Recommended Practice for the Design and Installation of Pressure-Relieving Systems in Refineries. Part I. 2d ed. (Sept).

American Petroleum Institute. 1962a.
Evaporation Loss From Fixed-Roof Tanks. Bulletin 2518 (June).

American Petroleum Institute. 1962b.
Evaporation Loss From Floating-Roof Tanks. Bulletin 2517 (Feb).

American Petroleum Institute. 1962c.
Evaporation Loss From Low-Pressure Tanks. Bulletin 2516 (Mar).

American Petroleum Institute. 1962d.
Use of Plastic Foam to Reduce Evaporation Loss. Bulletin 2515 (Jan).

American Petroleum Institute - American Society of Mechanical Engineers. 1951.
Unfired Pressure Vessel Code. 5th ed.

American Petroleum Institute. Division of Refining. 1951.
Manual on Disposal of Refinery Wastes. Vol III. Chemical Wastes. 2d ed. New York, N.Y.

American Petroleum Institute. Division of Refining. 1957.
Manual on Disposal of Refinery Wastes. Vol II. Waste Gases and Particulate Matter. 5th ed. New York, N. Y.

American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. 1963.
ASHRAE Guide and Data Book. New York, N. Y.

American Society of Mechanical Engineers. 1962.
ASME Unfired Pressure Vessel Code. Section VIII. New York, N. Y.

American Society for Testing Materials. 1958.
Specifications for Pig Lead, B29-55 In: 1958 Book of ASTM Standards, Part 2, Non-Ferrous Metals. Philadelphia, Pa.

American Society for Testing Materials. 1959.
Standard Method for Measurement of Odor in Atmospheres (Dilution Method). Designation D1391-57. In: ASTM Standards on Methods of Atmospheric Sampling and Analysis. Prepared by ASTM Committee D-22. Philadelphia, Pa.

American Water Works Association. 1951.
Standard Specifications for Coal-Tar Enamel Protective Coatings for Steel Water Pipe. New York, N. Y.

Anderson, E. 1944.
Some Factors and Principles Involved in the Separation and Collection of Dust, Mist and Fume From Gases. Trans. Am. Inst. Chem. Engrs., Part 1. 16:69-86.

Anderson, H.E. 1958.
Filtering Radioactive Particles From Stack Gas. Air Conditioning, Heating, and Ventilating. 55:71-77 (Feb).

Anderson, R.J. 1925.
The Metallurgy of Aluminium and Aluminium Alloys. Henry Cary Baird and Co., Inc., New York, N. Y.

Anderson, R.J. 1931.
Secondary Aluminum. The Sherwood Press, Inc., Cleveland, Ohio.

Andrews, A.I. 1961.
Porcelain Enamels. Garrard Press, Champaign, Ill.

Anonymous. 1950.
Repcal Brass Installs Unique Fume Control System. Western Metalworking. 8:32 (Mar).

Anonymous. 1957.
Metal Finishing-Guidebook-Directory. Metals and Plastics Publications, Inc., Westwood, N.J.

Anonymous. 1961.
1961 Petrochemical Handbook Indexes. Alkyl Aryl Sulfonates. Hydrocarbon Processing and Petroleum Refiner. 40:217 (Nov).

Arrandale, R.S. 1962.
Can Presintering Solve Glass Batch Problems? Ceram. Ind. 78:82, 83, 127, 138 (Apr).

ASHRAE Guide and Data Book.
See American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc. 1963.

The Asphalt Institute. 1954.
Asphalt Protective Coatings for Pipelines. College Park, Md.

The Asphalt Institute. 1957.
Specifications and Construction Methods for Hot-Mix Asphalt Paving for Streets and Highways. College Park, Md. (May).

Atomic Energy Commission.
See Ward, 1952.

Badger, W.L., and W.L. McCase. 1936.
Elements of Chemical Engineering. 2d ed. McGraw-Hill Book Co., Inc., New York, N. Y.

Bailey, T.W. 1957.
A Report on the Use of Silicone Lubricants at the Wheaton Glass Company. Glass Ind. 38:433-40 (Aug).

Baker, T.C. 1935.
Distillation and Absorption in Packed Columns. Ind. Eng. Chem. 27:977 (Aug).

Baque, H.W. 1954.
Cut Heating Costs 10% With Proper Insulation. Ceram. Ind. 62:77, 111 (Mar).

Barber, J.C. 1958.
Corrosion Problems in the Manufacture of Phosphoric Acid From Elemental Phosphorus. Corrosion. 14:21-26 (Aug).

Barker-Greene Company. 1960.
Drier Principles. Aurora, Ill.

Barnebey-Cheney Co.
Bulletin T-642. Columbus 19, Ohio.

Barnhart, D.H., and E.K. Diehl. 1960.
Control of Nitrogen Oxides in Boiler Flue Gases by Two-Stage Combustion. JAPCA. 10:397-406 (Oct).

Barry, H.M. 1960.
Fixed-Bed Adsorption. Chem. Eng. 67:105-07 (Feb 8).

Barth, E.J. 1958.
How to Make Roofing Asphalts. Petrol. Refiner. 37:172 (Mar).

Begeman, M.L. 1947.
Manufacturing Processes. 2d ed., John Wiley and Sons, Inc., New York, N.Y.

Benedict, M., and T.H. Pigford. 1957.
Nuclear Chemical Engineering. McGraw-Hill Book Co., Inc., New York, N.Y.

Beychok, M. 1953.
Build a Flare for Under $5000. Petrol. Processing. 8:1162-63 (Aug).

Bidlack, V.C., and E.W. Fasig. 1951.
Paint and Varnish Production Manual. John Wiley and Sons, New York, N. Y.

Bienstock, D., L.W. Brunn, E.M. Murphy, and H.E. Benson. 1958.
Sulfur Dioxide--Its Chemistry and Removal From Industrial Waste Gases. Bureau of Mines Information Circular 7836. U.S. Department of Interior, Washington, D.C.

Bienstock, D., and F.J. Field. 1960.
Bench-Scale Investigation on Removing Sulfur Dioxide From Flue Gases. JAPCA. 10:121-25 (Apr).

Bingham, J.E. 1958.
Check Your Procedures on Rupture Disc Installation. Chem. Eng. 65:143-45 (Apr 17).

Bodurtha, F.T., Jr. 1958.
Flare Stacks - How Tall? Chem. Eng. 65:177-80 (Dec 15).

Bonamassa, F., and Y.S. Yee. 1957.
Emission of Hydrocarbons to the Atmosphere From Cooling Towers. Report No. 5. Joint District, Federal, and State Project for the Evaluation of Refinery Emissions. Los Angeles County Air Pollution Control District. Los Angeles, Calif. (Aug).

Brandon, D. B. 1959.
Developing Mathematical Models for Computer Control. ISA Journal 6:70-73.

Brandt, A.D. . 1947.
Industrial Health Engineering. John Wiley and Sons, Inc., New York, N. Y.

Brief, R.S., A.H. Rose, and D.G. Stephan. 1956.
Properties and Control of Electric-Arc Steel Furnace Fumes. JAPCA. 6:220-24 (Feb).

Brink, J.A., Jr. 1959.
Monsanto Solves Air Pollution Problems With New Fiber Mist Eliminator. Chem. Eng. 66:183-86 (Nov 19).

Brown, C.O., and R.B. Wainright. 1952.
Synthetic Fluid Cracking Catalyst; Their Application and Utilization. Oil Gas J. 51(30):133-37.

Brown, G.W., and J.E. Sublett. 1957.
Union Oil Company Builds New Waste-Water Facilities. Ind. Water and Wastes. 2:6-8 (Jan-Feb).

Bruce, W.L., and W.A. Schubert. 1956.
Rotary Compressors and Vacuum Pumps. Chem. Eng. 63:224-26 (June).

Brumbaugh, A.K., Jr. 1947.
Smokeless Burning of Refinery Vent Gases. Petrol. Processing. 2:181.

Bulcraig, W.R., and J.B. Haigh. 1961.
The Reduction of Air Pollution During the Reversal of a Producer Gas-Fired Regenerative Glass Tank Furnace. J. Inst. Fuel. 34:73-78 (Feb).

Bussard, W.A. 1956.
Evaporation Losses and Their Control in Storage. Petrol. Processing. 11:104-26 (July).

Cameron, F. 1952.
Cottrell, Samaritan of Science. Doubleday and Co., Inc., Garden City, New York.

Campbell, W.W., and R.W. Fullerton. 1962.
Development of an Electric-Furnace Dust-Control System. JAPCA. 12:574-77, 590 (Dec).

Caplan, K.J. 1954.
A Self-Cleaning Air Filter. Chem. Eng. Progr. 50:409-14 (Aug).

Caplan, K.J. 1960.
Predicting the Performance of Reverse-Jet Filters. Air Conditioning, Heating, and Ventilating. 57:62-65 (Oct).

Carbon Products Division, Union Carbide Corporation. 1955.
Solvent Recovery by the "Columbia" Activated Carbon System. 270 Park Ave., New York, N. Y.

Case, E.L. 1956.
Reciprocating Compressors. Chem. Eng. 63:216-23 (June).

Castler, L.A., E.K. Daniels, and J.R. Lutz. 1956.
Pollution Control at Ferndale, Washington. Presented at 21st American Petroleum Institute Division of Refining Midyear Meeting, May 14-17, 1956.

Chass, R.L. 1959.
Engineering Control of Air Pollution in Los Angeles County. Presented at the Sanitary Engineering Division Program of the American Society of Civil Engineers, Los Angeles, Calif., Feb. 1959.

Chass, R.L., and R.E. George. 1960.
Contaminant Emissions From the Combustion of Fuels. JAPCA. 10:34-43 (Feb).

Chicago Bridge and Iron Company. 1959.
The Storage of Volatile Liquids. . Technical Bulletin No. 20. Oakbrook, Hinsdale P. O., Ill.

Chilton, C.H. 1949.
Cost Data Correlated. Chem. Eng. 46:97-106 (June).

Clapp, W.H., and S. Clark. 1944.
Engineering Materials and Processes. International Textbook Co., Scranton, Pa.

Clarke, L. 1947.
Manual for Process Engineering Calculations. McGraw-Hill Book Co., Inc., New York, N.Y.

Claude, R.E. 1956.
Axial Compressors. Chem. Eng. 63:212-15 (June).

Clement, R.L. 1961.
Selection, Application and Maintenance of Cloth Dust Filters. Plant Eng. 15:92-97 (Aug).

Cleveland, D.L. 1952.
Design and Operation of a Steam Inspirating Flare. Presented at 17th American Petroleum Institute Division of Refining Midyear Meeting, May 13, 1952.

Committee on Industrial Ventilation. 1960.
Industrial Ventilation. 6th ed. American Conference of Governmental Industrial Hygienists, Lansing, Mich. (4th ed., 1956; 7th ed., 1962)

Conison, J. 1960.
How to Design a Pressure Relief System. Chem. Eng. 67:109-14 (July 25).

Cornell, D., W.G. Knapp, and J.R. Fair. 1960.
Mass Transfer Efficiency - Packed Columns. Pts. 1 and 2. Chem. Eng. Progr. 56:68-74 (July); 48-53 (Aug).

Cottrell Electrical Precipitators.
See Western Precipitation Corporation, 1952.

Coulter, R.S. 1954.
Smoke, Dust, Fumes Closely Controlled in Electric Furnaces. Iron Age. 173:107-10 (Jan 14).

Cowan, D.W., H.J. Thompson, H.J. Paulus, and P.W. Mielke, Jr. 1963.
Bronchial Asthma Associated With Air Pollutants From the Grain Industry. JAPCA. 13:546-52 (Nov).

Crabaugh, H.R., A.H. Rose, Jr., and R.L. Chass. 1954.
Dust and Fumes From Gray Iron Cupolas--How They Are Controlled in Los Angeles County. Air Repair. 4:125-30 (Nov).

Crane Company. 1957.
Flow of Fluids. Technical Paper No. 410. Chicago, Ill.

Creesey, M.S., and A.K. Lyle. 1956.
What's New in Container Plant Design. Ceram. Ind. 67:98-101 (Sept).

Crumley, P.H., and A.W. Fletcher. 1956.
The Formation of Sulphur Trioxide in Flue Gases. J. Inst. Fuel. 29:322-27 (Aug).

Cumiskey, J.E. 1956.
Reciprocating Compressor Special Report, Introduction to Principles. Petrol. Refiner. 35:120-23 (Nov).

Dalla Valle, J.M. 1952.
Exhaust Hoods. 2d ed. The Industrial Press, New York, N.Y.

Dalla Valle, J.M., and H.C. Dudley. 1939.
Evaluation of Odor Nuisances in Manufacturing of Kraft Paper. Public Health Repts. 54:35-43 (Jan 13).

Decker, W.H. 1950.
Safe, Smokeless Combustion Features Waste Gas Burner at Sinclair Refinery. Petrol. Processing. 5:965-66, 968 (Sept).

Deckert, I.S., R.G. Lunche, and R.C. Murray. 1958.
Control of Vapors From Bulk Gasoline Loading. JAPCA. 8:223-33 (Nov).

de Lorenzi, O. 1947.
Combustion Engineering. Combustion Engineering--Superheater, Inc., New York, N. Y. (de Lorenzi, O., 1947. Courtesy Peabody Engineering Corp.).

Des Jardins, P.R. 1956.
Handling Compressible Fluids in Chemical Processing. Chem. Eng. 63:178-87 (June).

Deutsch, W. 1922.
Movement and Charge of Electrical Carriers in a Cylindrical Condenser. Ann. Physik, 68, 4th Ser. (373, orig. ser.):335-44.

Diehl, J.E. 1957.
Calculate Condenser Pressure Drop. Petrol. Refiner. 36:147-53. (Oct).

Dolman, R.E. 1952.
Pumps. Chem. Eng. 59:155-69 (Mar).

Donahue, D.A. 1956.
Heat Exchangers. Petrol. Processing. 11:102-32 (Mar).

Dow Chemical Co. 1963.
Dowtherm Handbook. Midland, Mich.

Drinker, P., and T. Hatch. 1954.
Industrial Dust. 2d ed. McGraw-Hill Book Co., Inc., New York, N.Y.

Driskell, L.R. 1960.
Design Tips for Piping of Pressure Relief Devices. Petrol. Refiner. 39:127-32 (July).

Duecker, W.W., and J.R. West. 1959.
Manufacture of Sulfuric Acid. 1st ed. Reinhold Publishing Corp., New York, N. Y.

Eastwood, L.W. 1946.
Gas in Light Alloys. John Wiley and Sons, New York, N. Y.

Edmister, W.C. 1948.
Hydrocarbon Absorption and Fractionation Process Design Methods. Petrol. Engr. 20(3):193-98, 200 (Dec).

Elliott, J., N. Kayne, and M. Le Duc. 1961.
Experimental Program for the Control of Organic Emissions From Protective Coating Operations. Report No. 8. Los Angeles County Air Pollution Control District, Los Angeles, Calif. (Jan).

Elonka, S. 1955.
Manual on Packing. Power. 99:107-30 (Mar).

Elonka, S. 1956.
Manual on Mechanical Seal. Power. 100:109-32 (Mar).

Environmental Sciences and Engineering, Division of Air Pollution.
Control of Particulate Emissions (Training Course Manual). Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio.

Ermenc, E.D. 1956.
Wisconsin Process Pebble Furnace Fixes Atmospheric Nitrogen. Chem. Eng. Progr. 52.149 (Apr).

Ezekiel, M. 1941.
Methods of Correlation Analysis. 2d ed. John Wiley and Sons, Inc., New York, N.Y.

Fabrianio, W.L. 1961.
How to Combat Checker Clogging and Carry-Over. Ceram. Ind. 77:102, 103, 127 (Sept).

Fairlie, A.M. 1936.
Sulfuric Acid Manufacture. 5th ed. Reinhold Publishing Corp., New York, N. Y.

Fairs, G.L. 1958.
High Efficiency Fibre Filters for the Treatment of Fine Mists. Trans. Inst. Chem. Engrs. 36:476-85.

Faith, W.L., N.A. Renzetti, and L.H. Rogers. 1957.
Third Technical Progress Report, Report No. 17. Air Pollution Foundation, Los Angeles, Calif. (Mar).

Field, J.H., L.M. Brunn, W.P. Haynes, and H.E. Benson. 1957.
Cost Estimates of Liquid-Scrubbing Processes for Removing Sulfur Dioxide From Flue Gases. JAPCA. 7:109-15 (Aug).

Filter Fabric Facts.
See Willington Sears Co., 1954.

Fischer, J. 1957.
Air Conveying of Dry Materials. Northwest. Miller (Minneapolis, Minn.). Dec 31, 1957.

Fischer, J. 1958.
Practical Pneumatic Conveyor Design. Chem. Eng. 65:114-18 (June 2).

Fisher, M.M., and F.C. Moriarty. 1953.
Waste Disposal in Urban Areas. Industry and Power (St. Joseph, Mich.). 64:83-85 (Apr).

Fox, E.A., and V.E. Gey. 1957.
Procedure for Measuring Odor Concentration in Air and Gases. JAPCA. 7:60-61 (May).

Frankenburg, T.T. 1963.
Air Pollution From Power Plants and Its Control. Combustion. 34(8):28-31 (Feb).

Frederick, E.R. 1961.
How Dust Filter Selection Depends Upon Electrostatics. Chem. Eng. 68:107 (June 26).

Friedlander, S.K., L. Silverman, P. Drinker, and M.W. First. 1952.
Handbook on Air Cleaning. U.S. Atomic Energy Commission, Washington, D.C. (Sept). (AECD-3361; NYO-1572).

Friedman, S.H. 1959.
Use These Computation Shortcuts. Chem. Eng. 66:149-50 (Sept 21).

Friedman, S.J., and W.R. Marshall, Jr. 1949.
Studies in Rotary Drying. Chem. Eng. Progr. 45:482 (Aug).

Gilbert, N., and F. Daniels. 1948.
Fixation of Atmospheric Nitrogen in a Gas Heated Furnace. Ind. Eng. Chem. 40:1719-23 (Sept).

Gillespie, G.R., and H.F. Johnstone. 1955.
Particle Size Distribution in Some Hygroscopic Aerosols. Chem. Eng. Prog. 51:78 (Feb).

Glasstone, S. 1946.
Textbook of Physical Chemistry. D. Van Nostrand Co., Inc., Princeton, N.J.

Glaubitz, F. 1963.
The Economic Combustion of Sulfur-Containing Heating Oil. Parts I and II. Combustion. 34(7):31-35 (Jan); 34(9):25-32 (Mar).

Gosline, C.A., L.L. Falk, and E.N. Helmers. 1956.
Evaluation of Weather Effects Section 5. In: Air Pollution Handbook. McGraw-Hill Book Co., Inc., New York, N.Y.

Green, W.G. 1952.
Smokeless Burning of Refinery Vent Gases. Presented at 17th American Petroleum Institute Division of Refining Midyear Meeting, May 13, 1952.

Griswold, J. 1946.
Fuels, Combustion, and Furnaces. 1st ed. McGraw-Hill Book Co., Inc., New York, N.Y.

Griswold, S.S., and I. Weisburd, eds. 1962.
Air Pollution Control Field Operations Manual Guide for Inspection and Enforcement. Public Health Service Publication No. 937. Division of Air Pollution, Public Health Service, U.S. Department of Health, Education, and Welfare, Washington, D.C.

Gumz, W. 1950.
Overfire Air Jets in European Practice. Combustion. 22:39-48 (Apr).

Gunsaulus, R.K. 1958.
How to Record and Control Furnace Flue Gas Automatically. Ceram. Ind. 70:70-73, 93, 95 (Mar).

Haagen-Smit, A.J. 1958.
Studies of Air Pollution Control by Southern California Edison Company. JAPCA. 7:251-55 (Feb).

Hajek, J.D., and E.E. Ludwig. 1960.
How to Design Safe Flare Stacks. Parts I and II. Petrol. Engr. 32:C31-C38; C44-C51 (June, July).

Haley, R.H. 1949.
How to Control Fumes in Non-Ferrous Melting. Foundry. 77:118, 121 (Sept).

Hannaman, J.R., and A.J. Etingen. 1956.
Here's a Workable Smokeless Flare System. Petrol. Processing. 11:66-69 (Mar).

Hauck Manufacturing Company. 1953.
Industrial Combustion Data. Brooklyn, N.Y.

Hemeon, W.C.L. 1955.
Plant and Process Ventilation. 1st ed. The Industrial Press, New York, N.Y. (2d ed, 1963).

Hansen, J.E. 1932.
The Advanced Technique of Porcelain Enameling. Enamelist Publishing Co., Cleveland, Ohio.

Herrick, R.A. 1963.
A Baghouse Test Program for Oxygen Lanced Open Hearth Fume Control. JAPCA. 13:28-32 (Jan).

Hersey, H.J., Jr. 1955.
Reverse-Jet Filters. Ind. Chemist. 31:138 (Mar).

Hicks, T. 1951.
Power's Handbook on Fans. Power. 95:87-102 (Oct).

Holzbock, W.G. 1959.
Control Valve Construction. Chem. Eng. 66:135-38 (Apr 6).

Hougen, O.A., and K.M. Watson. 1945.
Industrial Chemical Calculations. 2d ed. John Wiley and Sons, Inc., New York, N.Y.

How, H. 1956.
How to Design Barometric Condensers. Chem. Eng. 63:174-82 (Feb).

Huebner, W.O. 1959.
How Esso Cuts Flare Gas Losses. Air Eng. 1:38-39 (Apr).

Hunter, W.L. 1959.
Bottom-Loading Tank Trucks Successful. Petrol. Refiner. 38:171-72. (Oct).

Industrial Hygiene Codes Committee. 1938.
Fundamentals of Design, Construction, Operation and Maintenance of Exhaust Systems. American Foundrymen's Association, Chicago, Ill. (Des Plaines, Ill.)

Industrial Ventilation.
See Committee on Industrial Ventilation, 1960.

Ingels, R.M., N.R. Shaffer, and J.A. Danielson. 1960.
Control of Asphaltic Concrete Plants in Los Angeles County. JAPCA. 10:29-33 (Feb).

Jenny, J.P. 1951.
Smelter Fume Control. Proceedings of Forty-Fourth Annual Convention, Air Pollution and Smoke Prevention Association of America (Air Pollution Control Association), Roanoke, Va., May 7-10, 1951.

Jensen, L. B. 1945.
Microbiology of Meats. 2d ed. Garrard Press, Champaign, Ill.

Johnstone, H.F., and M.H. Roberts. 1949.
Deposition of Aerosol Particles From Moving Gas Streams. Ind. Eng. Chem. 41:2417-23 (Nov).

Jones, C.T., and P.S. Viles. 1952.
Estimating Oil Losses by Atmospheric Evaporation From Refinery Separator Surfaces. Petrol. Refiner. 31:117-20 (Jan).

Kane, John M. _____.
Manual of Exhaust Hood Designs. Vol. 2. Bull. No. 270-E2B. American Air Filter Co., Inc., Louisville, Ky. 40208.

Kanter, C.V., R.G. Lunche, F. Bonamassa, B.J. Steigerwald, and R.K. Palmer. 1958.
Emissions to the Atmosphere From Petroleum Refineries in Los Angeles County. Report No. 9. Joint District, Federal, and State Project for the Evaluation of Refinery Emissions. Los Angeles County Air Pollution Control District, Los Angeles, Calif.

Kent, R.T. ed. 1938.
Mechanical Engineers Handbook. 11th ed. John Wiley and Sons, Inc, New York, N.Y. (12th ed., 1950).

Kern, D.Q. 1950.
Process Heat Transfer. McGraw-Hill Book Co., Inc., New York, N.Y.

Kerns, G.D. 1960.
New Charts Speed Drum Sizing. Petrol. Refiner. 39:168-70 (July).

Kirk, R.E., and D.F. Othmer. eds. 1947.
Encyclopedia of Chemical Technology. 1st ed. Interscience Encyclopedia, Inc., New York, N.Y. (Volumes 2, 5, 7, 8, 9, 10, and 14).

Krenz, W.B., R.C. Adrian, and R.M. Ingels. 1957.
Control of Solvent Losses in Los Angeles County. Proceedings of the Golden Jubilee Meeting of Air Pollution Control Association, St. Louis, Mo., June 2-6, 1957.

Lapple, C.E. 1951.
Processes Use Many Collection Types. Chem. Eng. 58:145-51 (May).

Lapple, C.E. 1963.
Dust and Mist Collection. In: Chemical Engineers' Handbook. Perry, J.H., ed. McGraw-Hill Book Co., Inc. See also, Air Pollution Abatement Manual. C.A. Gosline, ed. Manufacturing Chemists' Association, Inc., Washington, D.C. 1952.

Lemke, E.E., W.F. Hammond, and G. Thomas. 1960.
Air Pollution Control Measures for Hot Dip Galvanizing Kettles. JAPCA. 10(1):70-76 (Feb).

Leonard, E.S. 1956.
Centrifugal Compressors. Chem. Eng. 63:206-11 (June).

Leva, M. 1953.
Tower Packings and Packed Tower Design. The United States Stoneware Co. Akron, Ohio.

Liberman, J.A. 1957.
Engineering Aspects of the Disposal of Radioactive Wastes From the Peace-Time Applications of Nuclear Technology. Am. J. Public Health. 47:345-51 (Mar).

Lieblich, N. 1953.
Selection of Diaphragm Control Valves and Regulators. Proceedings of the Southwestern Gas Measurement Short Course, University of Oklahoma.

Lobo, W.E., L. Friend, F. Hashmall, and F. Zenz. 1945.
The Limiting Capacity of Dumped Tower Packings. Trans. Am. Inst. Chem. Engrs. 41:693-710.

Los Angeles County Air Pollution Control District. 1960a.
Organization and Program. Report No. 1. Emissions of Oxides of Nitrogen From Stationary Sources in Los Angeles County. Los Angeles, Calif.

Los Angeles County Air Pollution Control District. 1960b.
Oxides of Nitrogen Emitted by Small Sources. Report No. 2. Emissions of Oxides of Nitrogen From Stationary Sources in Los Angeles County. Los Angeles, Calif. (Sept).

Los Angeles County Air Pollution Control District. 1963.
Summary of Air Pollution Statistics. Los Angeles, Calif. (Jan).

Lowenstein, J.G. 1958.
Calculate Adequate Rupture Disc Size. Chem. Eng. 65:157-58 (Jan 13).

Lunche, R.G., A. Stein, C.J. Seymour, and R.L. Weimer. 1957.
Distribution Survey of Products Emitting Organic Vapors in Los Angeles County. Chem. Eng. Prog. 53:371-76 (Aug).

Lunde, K.E., and C.E. Lapple. 1957.
Dust and Mist Collection--A Critique on the State of the Art. Chem. Eng. Prog. 53:385-91 (Aug).

MacKnight, R.J., J.E. Williamson, J.J. Sableski, Jr., and J.O. Dealy. 1960.
Controlling the Flue-Fed Incinerator. JAPCA. 10:103-09 (Apr).

MacPhee, R.D., J.R. Taylor, and A.L. Chaney. 1957.
Some Data on Particulates From Fuel Oil Burning. Proceedings of Semi-Annual Technical Conference, Air Pollution Control Association, San Francisco, Calif., Nov. 18-19, 1957.

Magill, P.L., F.R. Holden, and C. Ackley, eds. 1956.
Air Pollution Handbook. McGraw-Hill Book Co., Inc., New York, N.Y.

Mantell, C.L. 1961.
Adsorption. 2d ed. McGraw-Hill Book Co., Inc., New York, N.Y.

Manual of Exhaust Hood Designs.
See Kane, J.M.

Manufacturing Chemists' Association, General Safety Committee. 1954.
Guide for Safety in the Chemical Laboratory. Van Nostrand, New York, N.Y.

Marks, L.S., ed. 1951.
Mechanical Engineers' Handbook. 5th ed. McGraw-Hill Book Co., Inc., New York, N.Y.

Marshall, W.R., Jr., and S.J. Friedman. 1950.
Drying. In: Chemical Engineers' Handbook, 3d ed. Perry, J.H., ed. McGraw-Hill Book Co., Inc., New York, N.Y.

Marzocchi, A., F. Lachut, and W.H. Willis, Jr. 1962.
Glass Fibers and Their Use as Filter Media. JAPCA. 12:38-42 (Jan).

Mason-Neilan Division. 1963.
Valve Slide Rule Instructions. Worthington Corp., Norwood, Mass.

Mattiello, J.J. 1943.
Protective and Decorative Coatings. Vol. III. John Wiley and Sons, New York, N.Y.

McAdams, W.H. 1942.
Heat Transmission. 2d ed. McGraw-Hill Book Co., Inc., New York, N.Y.

McCabe, L.C. 1952.
Secondary Processing of Aluminum. Ind. Eng. Chem. 44:121A-122A (May).

McCord, C.P., and W.N. Witheridge. 1949.
Odors, Physiology and Control. McGraw-Hill Book Co., Inc., New York, N.Y.

McLouth, M.E., and H.J. Paulus. 1961.
Air Pollution From the Grain Industry. JAPCA. 11:313-17 (July).

Mellan, I. 1944.
Industrial Solvents. Reinhold Publishing Corp., New York, N.Y.

Mellan, I. 1957.
Handbook of Solvents. Reinhold Publishing Corp., New York, N.Y.

Merritt, F.H. 1958.
Side Port Furnaces. Glass Ind. 39:375-96 (July).

Miller, P.D., Jr., E.J. Hibshman, and J.R. Connell. 1956.
The Design of Smokeless, Nonluminous Flares. Presented at 21st American Petroleum Institute Division of Refining Midyear Meeting, May 14-17, 1956.

Mills, J.L., W.F. Hammond, and R.C. Adrian. 1960.
Design of Afterburners for Varnish Cookers. JAPCA. 10:161-68 (Apr).

Mills, J.L., K.D. Luedtke, P.F. Woolrich, and L.B. Perry. 1961.
A Summary of Data on Air Pollution by Oxides of Nitrogen Vented From Stationary Sources. Final Report. Report No. 4. Emissions of Oxides of Nitrogen From Stationary Sources in Los Angeles County. Los Angeles, Calif. (July).

Mills, J.L., R.T. Walsh, K.D. Luedtke, and L.K. Smith. 1963.
Quantitative Odor Measurement. JAPCA. 13:467-75 (Oct).

Molcohy, B.D. 1950.
The Cupola--Its Raw Materials and Operation. Foundry. 78:75-76 (Mar).

Molos, J.E. 1961.
Control of Odors From a Continuous Soap Making Process. JAPCA. 11:9-13, 44 (Jan).

Monstross, C.F. 1953.
Entrainment Separation. Chem. Eng. 60:213-36 (Oct).

Mumford, A.R., et al. 1940.
Characteristics of Cloth Filters on Coal Dust-Air Mixtures. Trans. Am. Soc. Mech. Engrs. 62:271-81.

National Bureau of Standards. 1949.
Safe Handling of Radioactive Isotopes. Handbook No. 42.

National Fire Protection Association. 1963.
Standard for Ovens and Furnaces (NFPA No. 86A). 60 Batterymarch Street, Boston, Mass.

Natural Gas Equipment, Inc. 1955.
Venturi-Type Burner Catalog. 1810 Fair Oaks Ave., South Pasadena, Calif.

Natural Gas Processors Suppliers Association. 1957.
Engineering Data Book. 7th ed. Tulsa, Okla.

Neimeyer, E.R. 1961.
Check These Points When Designing Knockout Drums. Hydrocarbon Process. Petrol. Refiner. 40:155-56 (June).

Nelson, W.L. 1953.
How Painting Affects Storage Tank Losses. Oil Gas J. 52:130 (Nov 2).

Nelson, W.L. 1958.
Petroleum Refinery Engineering. 4th ed. McGraw-Hill Book Co., Inc., New York, N.Y.

New York Blower Company. 1948.
Bulletin 482, La Porte, Ind.

Niven, W.W., Jr. 1955.
Industrial Detergency. Reinhold Publishing Corp., New York, N.Y.

Nonferrous Foundrymen's Smog Committee. _____.
Furnace Practice Manual, Los Angeles, California.

The North American Manufacturing Co. 1952.
Combustion Handbook. Cleveland, Ohio.

Obrzut, J.J. 1958.
Will the Big Demand for Oxygen Come From Open Hearths? Iron Age. 182(Pt. 2):172-74 (Sept 11).

O'Connell, H.E. 1946.
Plate Efficiency of Fractionating Columns and Absorbers. Trans. Am. Inst. Chem. Engrs. 42:741-55.

Oil and Gas Journal. 1957.
Special Processing Section: Processing in Today's Refineries. Oil Gas J. 55:121-68 (Mar 25).

Oxy-Catalyst, Inc. 1956.
Oxycat Technical Manual. Berwyn, Pa. (Jan).

Parmelee, C.W. 1951.
Ceramic Glazes. 2d ed. Industrial Publications, Inc., Chicago 3, Ill.

Peach, N. 1959.
Electrical Conversion. Power. 103:67-90 (Dec).

Peckham, G.W. 1962.
New Electric Furnace Reduces Melting Costs. Glass Ind. 43:552, 568, 573 (Oct).

Penney, G.W. 1937.
A New Electrostatic Precipitator. Elec. Eng. 56:159-63 (Jan).

Perry, J.H., ed. 1950.
Chemical Engineers' Handbook. 3d ed. McGraw-Hill Book Co., Inc., New York, N.Y.

Peters, M.S. 1955a.
Principles and Processes for Removing Nitrogen Oxides From Gases. Engineering Experiment Station. University of Illinois. Technical Report No. 14 (Aug).

Peters, M.S. 1955b.
Stop Pollution by Nitrogen Oxides. Chem. Eng. 62:197 (May).

Plastics Catalog Corporation. 1959.
Modern Plastics Encyclopedia Issue for 1960. 37(1A):68-180. Bristol, Conn.

Porter, E.D. 1959.
Electric Furnaces. Chem. Eng. 66:133-36 (Mar 9).

Powell, J.S. 1950.
Selection of an Odorant for Natural Gas Odorization. Proceedings of Pacific Coast Gas Association. 41:134-38.

Prater, N.H., and J. Mylo. 1961.
Equipment Cost Data File. Hydrocarbon Process. Petrol. Refiner. 40:209-10 (May); 173-74 (June); 163-64 (July); 131-32 (Aug).

Priestley, H. 1958.
Introductory Physics. Allyn and Bacon, Inc., Boston, Mass.

Pring, R.T. 1952.
Bag-Type Cloth Dust and Fume Collectors. In: United States Technical Conference on Air Pollution, May 3-5, 1950, Washington, D.C., L.C. McCabe, chairman. McGraw-Hill Book Co., Inc., New York, N.Y.

Puleo, P.A. 1960.
Which to Use--Relief Valve or Rupture Disc? Petrol. Refiner. 39:157-62 (Oct).

Randolph, W.W. 1956.
Gas Distribution in Electrostatic Precipitators. Proceedings for Engineering Seminar on Electrostatic Precipitation. Pennsylvania State University, University Park, Pa.

Ranz, W.E. 1951.
The Impaction of Aerosol Particles on Cylindrical and Spherical Collectors. Engineering Experiment Station, University of Illinois, Technical Report No. 3. (March 31).

Rees, R.L. 1955.
The Removal of Sulfur Dioxide From Power-Plant Stack Gases. In: International Congress on Air Pollution. Problems and Control of Air Pollution. F.S. Mallette, ed. Reinhold Publishing Corp., New York, N.Y.

Rendle, L.K., and R.D. Wilsdon. 1956.
The Prevention of Acid Condensation in Oil-Fired Boilers. J. Inst. Fuel. 29:372-80 (Sept).

Reno, G.J., E.D. Neumann, and L.C. Burroughs. 1958.
How Shell Treats Refinery Wastes. Petrol. Refiner. 37:153-60 (May).

Report No. 3, Experimental Program for the Control of Organic Emissions From Protective Coating Operations. See Spencer et al., 1959.

Report No. 8, Experimental Program for the Control of Organic Emissions From Protective Coating Operations. See Elliott et al., 1961.

Research-Cottrell, Inc.
Velocity Tables. Bound Brook, N.J., (p. 1).

Robertson, L.F., F.V. Halvonik, and J.J. McMackin. 1957.
Regenerator Efficiency and Basic Brick in a Glass Furnace. Am. Ceram. Soc. Bull. 36:381-84 (Nov).

Rodebush, W.H. 1950.
Filtration of Aerosols. Chapter 9. In: Handbook on Aerosols. U.S. Atomic Energy Commission, Washington, D.C., 1950. Reprinted 1963 (Available From U.S. Department of Commerce, Office of Technical Services).

Ronald, D. 1935.
Handbook of Offensive Trades. William Hodge and Co., Ltd., London, Eng.

Rose, A.H., and H.R. Crabaugh. 1955.
Incinerator Design Standards: Research Findings. Publication 60. Los Angeles County Air Pollution Control District, Los Angeles, Calif.

Rose, A.H., Jr., D.G. Stephan, and R.L. Stenburg. 1958.
Prevention and Control of Air Pollution by Process Changes or Equipment. Tech. Rept. A58-11. Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio; See also, Air Pollution World Health Organization Monograph Series No. 46, Columbia University Press, New York, N.Y., 1961.

Rose, H.E., and A.J. Wood. 1956.
An Introduction to Electrostatic Precipitation in Theory and Practice. Essential Books, Fairlawn, N.J.

Rudolfs, W. 1953.
Industrial Water and Wastes, Their Disposal and Treatment. Reinhold Publishing Corp., New York, N.Y.

Rupp, W.H. 1956.
Air Pollution Sources and Their Control. Section 1. In: Air Pollution Handbook. McGraw-Hill Book Co., Inc., New York, N.Y.

St. John, H.M. 1955.
Melting Practice in the Brass Foundry. Foundry. 83:107-08 (Nov).

Samans, W. 1955.
Pressure Relief Devices. Petrol. Processing. 10:849-53 (June).

Sax, N.R. 1963.
Dangerous Properties of Industrial Materials. 2d ed. Reinhold Publishing Corp. New York, N. Y.

Scheer, J.F. 1956.
The Big Etch. Skyline (North American Aviation, Inc.). 14:23 (May).

Schmidt, A. 1928.
Progress in the Art of Electrical Precipitation. Trans. Am. Inst. Chem. Engrs. 21:11-33.

Schmidt, W.A. 1949.
Electrical Precipitation and Mechanical Dust Collection. Ind. Eng. Chem. 41:2428-32 (Nov).

Schmidt, W.A., and C.R. Flodin. 1952.
Fundamental Principles, Design, Application, Performance, and Limitations of Electrical Precipitation Equipment. In: United States Technical Conference on Air Pollution, May 3-5, 1950, Washington, D.C. L.C. McCabe, chairman. McGraw-Hill Book Co., New York, N.Y.

Schmidt, W.A., W.T. Sproull, and Y. Nakada. 1950.
How the Operation of a Cottrell Precipitator is Affected by the Resistivity of the Collected Material. Presented at 170th General Meeting, American Institute of Mining and Metallurgical Engineers, New York, N.Y., Feb. 15, 1950.

Selheimer, C.W., and R. Lance. 1954.
Analysis of Fumes Leaving Resin Kettles and Fume Abatement Equipment. Offic. Dig. Federation Paint and Varnish Production Clubs. 27:711-68 (Aug).

Semrau, K.T. 1960.
Correlation of Dust Scrubber Efficiency. JAPCA. 10:200-07 (June).

Sensenbaugh, J.D., and J. Jonakin. 1960.
Effects of Combustion Conditions on Nitrogen Oxide Formation in Boiler Furnaces. Paper No. 60-WA-334, American Society of Mechanical Engineers, New York, N.Y.

Shamos, M.H., and S.G. Roth. 1950.
Industrial and Safety Problems of Nuclear Technology. Harper Bros., New York, N.Y.

Shand and Jurs Co.
Bulletin 52-D. Berkeley, Calif.

Sharp, D.E. 1954.
Fuel Utilization in Glass Melting. Ceram. Ind. 63:45-51 (Dec).

Sharp, D.E. 1955.
Tank Design Aids in Melting and Fining. Ceram. Ind. 64:49-51, 88 (Feb).

Sherwood, T.K., and R.L. Pigford. 1952.
Absorption and Extraction. McGraw-Hill Book Co., Inc., New York, N.Y.

Shreve, R.N. 1945.
The Chemical Process Industries. 1st ed. McGraw-Hill Book Co., Inc., New York, N.Y. (2d ed., 1956).

Silverman, L. 1950.
Filtration Through Porous Materials. Am. Ind. Hyg. Assoc. Quart. 11:11-20.

Singer, S.J. 1956.
Silicones Open New Era in Glass Making. Ceram. Ind. 57:82, 83, 117 (Nov).

Slaik, H., and A. Turk. 1953.
Air Conservation Engineering. 2d ed. Connor Engineering Corp., Danbury, Conn.

Smith, A.G. 1956a.
Air Oxidation of Sulfides in Process Waters and Caustic Solutions. Presented at 21st American Petroleum Institute Division of Refining Midyear Meeting, May 14-17, 1956.

Smith, A.G. 1956b.
Ridding Process Waters and Caustic Solutions of Sulfides. Oil Gas J. 54:95-96, 98-99 (July 9).

Smith, E.C. 1958.
Air-Cooled Heat Exchangers. Chem. Eng. 65:145-50 (Nov 17).

Smolen, W.H. 1951.
Smokeless Flare Stacks. Petrol. Processing. 6:978-82 (Sept).

Smolen, W.H. 1952.
Design of Smokeless Flares. Presented at 17th American Petroleum Institute Division of Refining Midyear Meeting, May 13, 1952.

Spain, R.W. 1955.
Glass Furnaces and How They Operate. Ceram. Ind. 65:71-74 (Aug).

Spain, R.W. 1956a.
How to Get Better Results From Long Campaigns. Ceram. Ind. 67:84-85, 87 (Nov).

Spain, R.W. 1956b.
How to Control Poor Operating Conditions. Ceram. Ind. 67:80-83 (Dec).

Spaite, P.W., J.E. Hagan, and W.F. Todd. 1963.
A Protective Finish for Glass Fiber Fabrics. Chem. Eng. Progr. 59:54-57 (Apr).

Spaite, P.W., D.G. Stephan, and A.H. Rose, Jr. 1961.
High Temperature Fabric Filtration of Industrial Gases. JAPCA. 11:243-47 (May).

Spencer, E.F., Jr., N. Kayne, M.F. Le Duc, and J.H. Elliott. 1959.
Experimental Program for the Control of Organic Emissions From Protective Coating Operations. Report No. 3. Los Angeles County Air Pollution Control District, Los Angeles, Calif. (July).

Sproull, W.T. 1951.
Precipitators Stop Dust and Fumes. Chem. Eng. 58:151-54 (May).

Sproull, W.T., and Y. Nakada. 1951.
Operation of Cottrell Precipitators--Effects of Moisture and Temperature. Ind. Eng. Chem. 43:1350-58 (June).

Sproull, W.T. 1955.
Collecting High Resistivity Dusts and Fumes. Ind. Eng. Chem. 47:940-44 (Apr).

Stairmand, C.J. 1956.
The Design and Performance of Modern Gas-Cleaning Equipment. J. Inst. Fuel. 29:58-76 (Feb).

Steigerwald, B.J. 1958.
Emissions of Hydrocarbons to the Atmosphere From Seals on Pumps and Compressors. Report No. 6. Joint District, Federal, and State Project for the Evaluation of Refinery Emissions. Los Angeles County Air Pollution Control District, Los Angeles, Calif. (Apr).

Stenburg, R.L. 1958.
Control of Atmospheric Emissions From Paint and Varnish Manufacturing Operations. U. S. Department of Health, Education, and Welfare, Robert A. Taft Sanitary Engineering Center, Cincinnati, Ohio. Technical Report A58-4 (June). Also in: Paint and Varnish Production. 49:61-65, 111-14. (1959).

Stephan, D.G., and G.W. Walsh. 1960.
Residual Dust Profiles in -- Air Filtration. Ind. Eng. Chem. 52:999-1002 (Dec).

Stephan, D.G., G.W. Walsh, and R.A. Herrick. 1960.
Concepts in Fabric Air Filtration. Am. Ind. Hyg. Assoc. J. 21:1-14 (Feb).

Stern, A.C., K.J. Caplan, and P.D. Bush. 1956.
Removal of Particulate Matter From Gaseous Wastes: Cyclone Dust Collectors. Division of Refining, American Petroleum Institute, New York, N.Y.

Stine, V.F. 1955.
Blast Cleaning in Industry, Bulletin No. 1500. Pangborn Corporation, Hagerstown, Md.

Streeter, V.L. 1951.
Fluid Mechanics. McGraw-Hill Book Co., Inc., New York, N.Y.

Striplin, M.M., Jr. 1948.
Development of Processes and Equipment for Production of Phosphoric Acid. Chemical Engineering Report No. 2. Tennessee Valley Authority.

Sussman, V.H. 1957.
Atmospheric Emissions From Catalytic Cracking Unit Regenerator Stacks. Report No. 4. Joint District, Federal, and State Project for Evaluation of Refinery Emissions. Los Angeles County Air Pollution Control District, Los Angeles, Calif. (June).

Sussman, V.H., R.K. Palmer, F. Bonamassa, B.J. Steigerwald, and R.G. Lunche. 1958.
Emissions to the Atmosphere From Eight Miscellaneous Sources in Oil Refineries. Report No. 8. Joint District, Federal, and State Project for the Evaluation of Refinery Emissions. Los Angeles County Air Pollution Control District, Los Angeles, Calif. (June).

Suter, H.R. 1955.
Range of Applicability of Catalytic Fume Burners. JAPCA. 5(3):173 75, 184 (Nov).

Sutton, O.G. 1950.
The Dispersion of Hot Gases in the Atmosphere. J. Meteorol. 7:307-12 (Oct).

Teller, A.J. 1960.
Absorption With Chemical Reaction. Chem. Eng. 67:111-24 (July 11).

Thomas, J.W. 1959.
Air vs. Water Cooling, Cost Comparison. Chem. Eng. Progr. 55:38-41 (Apr).

Tooley, F.V. 1953.
Handbook of Glass Manufacture. Volumes I and II. Ogden Publishing Co., New York, N.Y.

Treybal, R.E. 1955.
Mass-Transfer Operations. McGraw-Hill Book Co., Inc., New York, N.Y.

Trinks, W. 1955.
Industrial Furnaces. Volume I. 3d ed. John Wiley and Sons, New York, N.Y.

Turk, A., and K.A. Bownes. 1951.
Adsorption Can Control Odors. Chem. Eng. 58:156-58 (May).

Underwood, G. 1962.
Removal of Sub-Micron Particles From Industrial Gases, Particularly in the Steel and Electricity Industries. Intern. J. Air Water Pollution. 6:229-63 (May-Aug).

U.S. National Bureau of Standards.
Fuel Oils. Commercial Standard CS-48. Clearinghouse for Federal Scientific and Technical Information, Springfield, Va. 22151.

U.S. National Bureau of Standards. 1949.
Handbook No. 42. Safe Handling of Radioactive Isotopes. Washington, D.C.

Van Dreser, M.L. 1962.
Basic Refractories for the Glass Industry. Glass Ind. 43:18-21 (Jan).

Von Fisher, W. 1948.
Paint and Varnish Technology. Reinhold Publishing Corp., New York, N. Y.

Waitkus, J. 1962.
Recover Waste Heat to Reduce Glass Tank Operating Cost. Ceram. Ind. 79:38-42, 68-70 (Dec).

Walker, E.A., and J.E. Coolidge. 1953.
Semiempirical Equation of Electrostatic Precipitation. Ind. Eng. Chem. 45:2417-22 (Nov).

Walker, W.H., W.K. Lewis, W.H. McAdams, and E.R. Gilliland. 1937.
Principles of Chemical Engineering. 3d ed. McGraw-Hill Publishing Co., Inc., New York, N.Y.

Walsh, G.W., and P.W. Spaite. 1962.
An Analysis of Mechanical Shaking in Air Filtration, JAPCA. 12:57-61 (Feb).

Ward, D.R. 1952.
Design of Laboratories for Safe Use of Radioisotopes. AECU-2226. U.S. Atomic Energy Commission Advisory Field Service Branch, Isotopes Division, Oak Ridge, Tenn. (Nov).

Watts, D.L., and J.F. Higgins. 1962.
The New Baghouse Installation for Cleaning Smelter Gases at Phelps Dodge Refining Corporation. JAPCA. 12:217-20 (May).

Weisburd.
See, Griswold, 1962.

Western Precipitation Corporation, 1952.
Cottrell Electrical Precipitators. 3d ed. Los Angeles, Calif.

White, H.J. 1951.
Particle Charging in Electrostatic Precipitation. Trans. Am. Inst. Elec. Engrs. 70(II):1186-91.

White, H.J. 1953.
Electrostatic Precipitators for Electric Generating Stations. Trans. Am. Inst. Elec. Engrs. 72(III):229-41.

White, H.J. 1957.
Fifty Years of Electrostatic Precipitation. JAPCA. 7:166-77 (Nov).

White, H.J. 1963.
Industrial Electrostatic Precipitation. Addison-Wesley Publication Co., Reading, Mass.

White, H.J., and W.H. Cole. 1960.
Design and Performance Characteristics of High-Velocity, High-Efficiency Air Cleaning Precipitators. JAPCA. 10:239-45 (June).

White, H.J., and G.W. Penney. 1961.
Basic Concepts. In: Electrical Precipitation Fundamentals. Proceedings for Engineering Seminar on Electrostatic Precipitation, June 17-21, 1957. Pennsylvania State University, Department of Electrical Engineering and General Extension, University Park, Pa.

Williams, C.E., et al. 1940.
Determination of Cloth Area for Industrial Air Filters. Heating, Piping, Air Conditioning. 12:259-63 (Apr).

Williams Patent Crusher and Pulverizer Co., Inc.
Bulletin 696. St. Louis 6, Mo.

Willington Sears Co. 1954.
Filter Fabric Facts. New York, N.Y.

Wilson, E.F. 1960.
Dust Control in Glass Manufacturing. Glass Ind. 41:202-03, 236, 237 (Apr).

Woodhouse, H. 1957.
Centrifugal Pump Packings and Seals. Pt. 3. Mechanical Seals. Petrol. Refiner. 36:207-11 (Apr).

Woodward, E.R., and E.R. Fenrich. 1952.
Odor Control With Chlorine Dioxide. Chem. Eng. 59:174-75 (Apr).

Zachariasen, W.H. 1932.
The Atomic Arrangement of Glass. J. Am. Chem. Soc. 54:3841-51.

John Zink Company.
Flare Bulletin. Tulsa, Okla.

APPENDIX A: RULES AND REGULATIONS

APPENDIX B: ODOR-TESTING TECHNIQUES

KARL D. LUEDTKE, Intermediate Air Pollution Engineer

APPENDIX C: HYPOTHETICAL AVAILABLE HEATS FROM NATURAL GAS

SANFORD M. WEISS, Senior Air Pollution Engineer

APPENDIX D: MISCELLANEOUS DATA

APPENDIX A

Except for format and the Contents, Appendix A was set in type exactly as it appears in Los Angeles APCD RULES AND REGULATIONS manual.

BLANK PAGE

APPENDIX A: RULES AND REGULATIONS

RULES AND REGULATIONS OF THE AIR POLLUTION CONTROL DISTRICT

REGULATION I. GENERAL PROVISIONS

RULE 1. TITLE

These rules and regulations shall be known as the rules of the Air Pollution Control District.

RULE 2. (Amended 1-16-58) DEFINITIONS

a. Except as otherwise specifically provided in these rules and except where the context otherwise indicates, words used in these rules are used in exactly the same sense as the same words are used in Chapter 2, Division 20 of the Health and Safety Code.

b. (Amended 1-16-58) Person. "Person" means any person, firm, association, organization, partnership, business trust, corporation, company, contractor, supplier, installer, user or owner, or any state or local governmental agency or public district or any officer or employee thereof.

c. Board. "Board" means the Air Pollution Control Board of the Air Pollution Control District of Los Angeles County.

e. Section. "Section" means section of the Health and Safety Code of the State of California unless some other statute is specifically mentioned.

f. Rule. "Rule" means a rule of the Air Pollution Control District of Los Angeles County.

g. (Amended 3-14-63) Los Angeles Basin. "Los Angeles Basin" is defined as being within the following described boundaries:

Beginning at the intersection of the southerly boundary of the Angeles National Forest with the easterly boundary of the County of Los Angeles; thence along said easterly boundary in a general southwesterly direction to the mean high tide line of the Pacific Ocean; thence continuing along the boundary of the County of Los Angeles (in the Pacific Ocean) in a general southwesterly, westerly and northwesterly direction to its most westerly intersection with the boundary of the City of Los Angeles (in the Pacific Ocean); thence in a general northerly direction along the generally westerly boundary of the City of Los Angeles to its most northerly intersection with the westerly boundary of the County of Los Angeles; thence in a general easterly direction along the northerly boundary of said City of Los Angeles to the southwesterly corner of Section 16, Township 2 North, Range 13 West, S. B. B. & M.; thence in a general easterly direction along said southerly boundary of the Angeles National Forest to said easterly boundary of the County of Los Angeles.

h. Regulation. "Regulation" means one of the major subdivisions of the Rules of the Air Pollution Control District of Los Angeles County.

i. (Amended 1-16-58) Particulate Matter. "Particulate Matter" is any material, except uncombined water, which exists in a finely divided form as a liquid or solid at standard conditions.

j. Process Weight Per Hour. "Process Weight" is the total weight of all materials introduced into any specific process which process may cause any discharge into the atmosphere. Solid fuels charged will be considered as part of the process weight, but liquid and gaseous fuels and combustion air will not. "The Process Weight Per Hour" will be derived by dividing the total process weight by the number of hours in one complete operation from the beginning of any given process to the completion thereof, excluding any time during which the equipment is idle.

k. Dusts. "Dusts" are minute solid particles released into the air by natural forces or by mechanical processes such as crushing, grinding, milling, drilling, demolishing, shoveling, conveying, covering, bagging, sweeping, etc.

l. Condensed Fumes. "Condensed Fumes" are minute solid particles generated by the condensation of vapors from solid matter after volatilization from the molten state, or may be generated by sublimation, distillation, calcination, or chemical reaction, when these processes create air-borne particles.

m. Combustion Contaminants. "Combustion Contaminants" are particulate matter discharged into the atmosphere from the burning of any

kind of material containing carbon in a free or combined state.

n. Atmosphere. "Atmosphere" means the air that envelops or surrounds the earth. Where air pollutants are emitted into a building not designed specifically as a piece of air pollution control equipment, such emission into the building shall be considered an emission into the atmosphere.

o. Combustible Refuse (Amended 3-2-67) "Combustible Refuse" is any solid or liquid combustible waste material containing carbon in a free or combined state.

p. Multiple-Chamber Incinerator. "Multiple-chamber Incinerator" is any article, machine, equipment, contrivance, structure or part of a structure, used to dispose of combustible refuse by burning, consisting of three or more refractory lined combustion furnaces in series, physically separated by refractory walls, interconnected by gas passage ports or ducts and employing adequate design parameters necessary for maximum combustion of the material to be burned. The refractories shall have a Pyrometric Cone Equivalent of at least 17, tested according to the method described in the American Society for Testing Materials, Method C-24.

q. Oil-Effluent Water Separator. "Oil-effluent water separator" is any tank, box, sump or other container in which any petroleum or product thereof, floating on or entrained or contained in water entering such tank, box, sump or other container, is physically separated and removed from such water prior to outfall, drainage, or recovery of such water.

RULE 3. STANDARD CONDITIONS

Standard conditions are a gas temperature of 60 degrees Fahrenheit and a gas pressure of 14.7 pounds per square inch absolute. Results of all analyses and tests shall be calculated or reported at this gas temperature and pressure.

REGULATION II. PERMITS

RULE 10. PERMITS REQUIRED

a. Authority to Construct. (Amended 4-2-64) Any person building, erecting, altering or replacing any article, machine, equipment or other contrivance, the use of which may cause the issuance of air contaminants or the use of which may eliminate or reduce or control the issuance of air contaminants, shall first obtain authorization for such construction from the Air Pollution Control Officer. An authority to construct shall remain in effect until the permit to operate the equipment for which the application was filed is granted or denied or the application is canceled.

b. Permit to Operate. (Amended 11-16-54) Before any article, machine, equipment or other contrivance described in Rule 10(a) may be operated or used, a written permit shall be obtained from the Air Pollution Control Officer. No permit to operate or use shall be granted either by the Air Pollution Control Officer or the Hearing Board for any article, machine, equipment or contrivance described in Rule 10(a), constructed or installed without authorization as required by Rule 10(a), until the information required is presented to the Air Pollution Control Officer and such article, machine, equipment or contrivance is altered, if necessary, and made to conform to the standards set forth in Rule 20 and elsewhere in these Rules and Regulations.

c. Posting of Permit to Operate. (Amended 3-2-67) A person who has been granted under Rule 10 a permit to operate any article, machine, equipment, or other contrivance described in Rule 10(b), shall firmly affix such permit to operate, an approved facsimile, or other approved identification bearing the permit number upon the article, machine, equipment, or other contrivance in such a manner as to be clearly visible and accessible. In the event that the article, machine, equipment, or other contrivance is so constructed or operated that the permit to operate cannot be so placed, the permit to operate shall be mounted so as to be clearly visible in an accessible place within 25 feet of the article, machine, equipment or other contrivance, or maintained readily available at all times on the operating premises.

d. (Adopted 3-28-57) A person shall not wilfully deface, alter, forge, counterfeit, or falsify a permit to operate any article, machine, equipment, or other contrivance.

f. Permit to Sell or Rent. Adopted 1-16-58) Any person who sells or rents to another person an incinerator which may be used to dispose of combustible refuse by burning within the Los Angeles Basin and which incinerator is to be used exclusively in connection with any structure, which structure is designed for and used exclusively as a dwelling for not more than four families, shall first obtain a permit from the Air Pollution Control Officer to sell or rent such incinerator.

RULE 11. EXEMPTIONS

An authority to construct or a permit to operate shall not be required for:

a. (Amended 3-2-67) Vehicles as defined by the Vehicle Code of the State of California but not including any article, machine, equipment or other contrivance mounted on such vehicle that would otherwise require a permit under the provisions of these Rules and Regulations.

b. Vehicles used to transport passengers or freight.

c. Equipment utilized exclusively in connection with any structure, which structure is designed for and used exclusively as a dwelling for not more than four families.

d. The following equipment:

1. Comfort air conditioning or comfort ventilating systems which are not designed to remove air contaminants generated by or released from specific units or equipment.

2. Refrigeration units except those used as, or in conjunction with, air pollution control equipment.

3. (Amended 3-2-67) Piston type internal combustion engines.

5. Water cooling towers and water cooling ponds not used for evaporative cooling of process water or not used for evaporative cooling of water from barometric jets or from barometric condensers.

6. Equipment used exclusively for steam cleaning.

7. Presses used exclusively for extruding metals, minerals, plastics or wood.

8. Porcelain enameling furnaces, porcelain enameling drying ovens, vitreous enameling furnaces or vitreous enameling drying ovens.

9. Presses used for the curing of rubber products and plastic products.

10. Equipment used exclusively for space heating, other than boilers.

13. Equipment used for hydraulic or hydrostatic testing.

14. (Amended 7-28-66) All sheet-fed printing presses and all other printing presses using exclusively inks containing less than 10% organic solvents, diluents or thinners.

17. Tanks, vessels and pumping equipment used exclusively for the storage or dispensing of fresh commercial or purer grades of:

a. Sulfuric acid with an acid strength of 99 per cent or less by weight.
b. Phosphoric acid with an acid strength of 99 per cent or less by weight.
c. Nitric acid with an acid strength of 70 per cent or less by weight.

18. Ovens used exclusively for the curing of plastics which are concurrently being vacuum held to a mold or for the softening or annealing of plastics.

19. (Amended 6-1-65) Equipment used exclusively for the dyeing or stripping (bleaching) of textiles where no organic solvents, diluents or thinners are used.

20. (Amended 7-28-66) Equipment used exclusively to mill or grind coatings and molding compounds where all materials charged are in a paste form.

21. Crucible type or pot type furnaces with a brimful capacity of less than 450 cubic inches of any molten metal.

22. (Amended 6-1-65) Equipment used exclusively for the melting or applying of wax where no organic solvents, diluents or thinners are used.

23. Equipment used exclusively for bonding lining to brake shoes.

24. Lint traps used exclusively in conjunction with dry cleaning tumblers.

25. Equipment used in eating establishments for the purpose of preparing food for human consumption.

26. Equipment used exclusively to compress or hold dry natural gas.

27. Tumblers used for the cleaning or deburring of metal products without abrasive blasting.

28. Shell core and shell-mold manufacturing machines.

29. Molds used for the casting of metals.

30. (Amended 3-2-67) Abrasive blast cabinet-dust filter integral combination units where the total internal volume of the blast section is 50 cubic feet or less.

31. Batch mixers of 5 cubic feet rated working capacity or less.

32. Equipment used exclusively for the packaging of lubricants or greases.

33. (Amended 3-2-67) Equipment used exclusively for the manufacture of water emulsions of asphalt, greases, oils or waxes.

34. Ovens used exclusively for the curing of vinyl plastisols by the closed mold curing process.

35. Equipment used exclusively for conveying and storing plastic pellets.

36. Equipment used exclusively for the mixing and blending of materials at ambient temperature to make water based adhesives.

37. Smokehouses in which the maximum horizontal inside cross-sectional area does not exceed 20 square feet.

38. Platen presses used for laminating.

e. The following equipment or any exhaust system or collector serving exclusively such equipment:

1. Blast cleaning equipment using a suspension of abrasive in water.

2. Ovens, mixers and blenders used in bakeries where the products are edible and intended for human consumption.

3. Kilns used for firing ceramic ware, heated exclusively by natural gas, liquefied petroleum gas, electricity or any combination thereof.

4. Laboratory equipment used exclusively for chemical or physical analyses and bench scale laboratory equipment.

5. Equipment used for inspection of metal products.

6. Confection cookers where the products are edible and intended for human consumption.

7. Equipment used exclusively for forging, pressing, rolling or drawing of metals or for heating metals immediately prior to forging, pressing, rolling or drawing.

8. Die casting machines.

9. Atmosphere generators used in connection with metal heat treating processes.

10. Photographic process equipment by which an image is reproduced upon material sensitized to radiant energy.

11. Brazing, soldering or welding equipment.

12. Equipment used exclusively for the sintering of glass or metals.

13. (Amended 3-2-67) Equipment used for buffing (except automatic or semi-automatic tire buffers) or polishing, carving, cutting, drilling, machining, routing, sanding, sawing, surface grinding or turning of ceramic artwork, ceramic precision parts, leather, metals, plastics, fiberboard, masonry, asbestos, carbon or graphite.

14. (Amended 3-2-67) Equipment used for carving, cutting, drilling, surface grinding, planing, routing, sanding, shredding or turning of wood or the pressing or storing of sawdust, wood chips or wood shavings.

15. (Amended 3-2-67) Equipment using aqueous solutions for surface preparation, cleaning, stripping, etching (does not include chemical milling) or the electrolytic plating with, electrolytic polishing of, or the electrolytic stripping of brass, bronze, cadmium, copper, iron, lead, nickel, tin, zinc, and precious metals.

16. Equipment used for washing or drying products fabricated from metal or glass, provided that no volatile organic materials are used in the process and that no oil or solid fuel is burned.

17. Laundry dryers, extractors or tumblers used for fabrics cleaned only with water solutions of bleach or detergents.

19. Foundry sand mold forming equipment to which no heat is applied.

20. Ovens used exclusively for curing potting materials or castings made with epoxy resins.

21. Equipment used to liquefy or separate oxygen, nitrogen or the rare gases from the air.

22. Equipment used for compression molding and injection molding of plastics.

23. (Amended 6-1-65) Mixers for rubber or plastics where no material in powder form is added and no organic solvents, diluents or thinners are used.

24. Equipment used exclusively to package pharmaceuticals and cosmetics or to coat pharmaceutical tablets.

25. (Amended 6-1-65) Equipment used exclusively to grind, blend or package tea, cocoa, spices or roasted coffee.

26. (Amended 7-28-66) Roll mills or calenders for rubber or plastics where no organic solvents, diluents or thinners are used.

27. (Adopted 3-2-67) Vacuum producing devices used in laboratory operations or in connection with other equipment which is exempt by Rule 11.

f. Steam generators, steam superheaters, water boilers, water heaters, and closed heat transfer systems that are fired exclusively with one of the following:

1. Natural gas.

2. Liquefied petroleum gas.

3. A combination of natural gas and liquefied petroleum gas.

g. Natural draft hoods, natural draft stacks or natural draft ventilators.

h. Containers, reservoirs, or tanks used exclusively for:

1. (Amended 6-1-65) Dipping operations for coating objects with oils, waxes or greases where no organic solvents, diluents or thinners are used.

2. Dipping operations for applying coatings of natural or synthetic resins which contain no organic solvents.

3. Storage of liquefied gases.

5. Unheated storage of organic materials with an initial boiling point of 300°F. or greater.

6. The storage of fuel oils with a gravity of 25° API or lower.

7. The storage of lubricating oils.

8. The storage of fuel oils with a gravity of 40° API or lower and having a capacity of 10,000 gallons or less.

9. (Amended 3-2-67) The storage of organic liquids, except gasoline, normally used as solvents, diluents or thinners, inks, colorants, paints, lacquers, enamels, varishes, liquid resins or other surface coatings, and having a capacity of 6,000 gallons or less.

10. (Amended 3-2-67) The storage of liquid soaps, liquid detergents, vegetable oils, waxes or wax emulsions.

11. The storage of asphalt.

12. (Amended 6-1-65) Unheated solvent dispensing containers, unheated non-conveyorized solvent rinsing containers or unheated non-conveyorized coating dip tanks of 100 gallons capacity or less.

14. (Adopted 6-1-65) The storage of gasoline having a capacity of less than 250 gallons.

15. (Adopted 3-2-67) Transporting materials on streets or highways.

i. Equipment used exclusively for heat treating glass or metals, or used exclusively for case hardening, carburizing, cyaniding, nitriding, carbonitriding, siliconizing or diffusion treating of metal objects.

j. Crucible furnaces, pot furnaces or induction furnaces, with a capacity of 1000 pounds or less each, in which no sweating or distilling is conducted and from which only the following metals are poured or in which only the following metals are held in a molten state:

1. Aluminum or any alloy containing over 50 per cent aluminum.

2. Magnesium or any alloy containing over 50 per cent magnesium.

3. Lead or any alloy containing over 50 per cent lead.

4. Tin or any alloy containing over 50 per cent tin.

5. Zinc or any alloy containing over 50 per cent zinc.

6. Copper.

7. Precious metals.

k. Vacuum cleaning systems used exclusively for industrial, commercial or residential housekeeping purposes.

l. Structural changes which cannot change the quality, nature or quantity of air contaminant emissions.

m. Repairs or maintenance not involving structural changes to any equipment for which a permit has been granted.

n. Identical replacements in whole or in part of any article, machine, equipment or other contrivance where a permit to operate had previously been granted for such equipment under Rule 10.

RULE 12. (Amended 1-16-58) TRANSFER

An authority to construct, permit to operate or permit to sell or rent shall not be transferable, whether by operation of law or otherwise, either from one location to another, from one piece of equipment to another, or from one person to another.

RULE 13. BLANKET PERMITS. (Deleted 4-2-64)

RULE 14. (Amended 1-16-58) APPLICATIONS

Every application for an authority to construct, permit to operate or permit to sell or rent required under Rule 10 shall be filed in the manner and form prescribed by the Air Pollution Control Officer, and shall give all the information necessary to enable the Air Pollution Control Officer to make the determination required by Rule 20 hereof.

RULE 17. (Amended 6-1-65) CANCELLATION OF APPLICATIONS

a. (Amended 6-1-65) An authority to construct shall expire and the application shall be canceled two years from the date of issuance of the authority to construct.

b. (Amended 6-1-65) An application for permit to operate existing equipment shall be canceled two years from the date of filing of the application.

RULE 18. (Amended 1-16-58) ACTION ON APPLICATIONS

The Air Pollution Control Officer shall act, within a reasonable time, on an application for authority to construct, permit to operate or permit to sell or rent, and shall notify the applicant in writing of his approval, conditional approval or denial.

RULE 19. (Adopted 3-28-57) PROVISION OF SAMPLING AND TESTING FACILITIES

A person operating or using any article, machine, equipment or other contrivance for which these rules require a permit shall provide and maintain such sampling and testing facilities as specified in the authority to construct or permit to operate.

RULE 20. (Amended 3-14-63) STANDARDS FOR GRANTING APPLICATIONS

a. The Air Pollution Control Officer shall deny an authority to construct, permit to operate or permit to sell or rent, except as provided in Rule 21, if the applicant does not show that every article, machine, equipment or other contrivance, the use of which may cause the issuance of air contaminants, or the use of which may eliminate or reduce or control the issuance of air contaminants, is so designed, controlled, or equipped with such air pollution control equipment, that it may be expected to operate without emitting or without causing to be emitted air contaminants in violation of Sections 24242 or 24243, Health and Safety Code, or of these Rules and Regulations.

b. (Adopted 3-28-57) Before an authority to construct or a permit to operate is granted, the Air Pollution Control Officer may require the applicant to provide and maintain such facilities as are necessary for sampling and testing purposes in order to secure information that will disclose the nature, extent, quantity or degree of air contaminants discharged into the atmosphere from the article, machine, equipment or other contrivance described in the authority to construct or permit to operate. In the event of such a requirement, the Air Pollution Control Officer shall notify the applicant in writing of the required size, number and location of sampling holes; the size and location of the sampling platform; the access to the sampling platform; and the utilities for operating the sampling and testing equipment. The platform and access shall be constructed in accordance with the General Industry Safety Orders of the State of California.

c. (Adopted 6-25-59) In acting upon a Permit to Operate, if the Air Pollution Control Officer finds that the article, machine, equipment or other contrivance has been constructed not in accordance with the Authority to Construct, he shall deny the Permit to Operate. The Air Pollution Control Officer shall not accept any further application for Permit to Operate the article, machine, equipment or other contrivance so constructed until he finds that the article, machine, equipment or other contrivance has been reconstructed in accordance with the Authority to Construct.

RULE 21. (Amended 12-4-58) CONDITIONAL APPROVAL

a. The Air Pollution Control Officer may issue an authority to construct or a permit to operate, subject to conditions which will bring the operation of any article, machine, equipment or other contrivance within the standards of Rule 20, in which case the conditions shall be specified in writing. Commencing work under such an authority to construct or operation under such a permit to operate shall be deemed acceptance of all the conditions so specified. The Air Pollution Control Officer shall issue an authority to construct or a permit to operate with revised conditions upon receipt of a new application, if the applicant demonstrates that the article, machine, equipment or other contrivance can operate within the standards of Rule 20 under the revised conditions.

b. The Air Pollution Control Officer may issue a permit to sell or rent, subject to conditions which will bring the operation of any article, machine, equipment or other contrivance within the standards of Rule 20, in which case the conditions shall be specified in writing. Selling or renting under such a permit to sell or rent shall be deemed acceptance of all the conditions so specified. The Air Pollution Control Officer shall issue a permit to sell or rent with revised conditions upon receipt of a new application, if the applicant demonstrates that the article, machine, equipment or other contrivance can operate within the standards of Rule 20 under the revised conditions.

RULE 22. (Amended 1-16-58) DENIAL OF APPLICATIONS

In the event of denial of an authority to construct, permit to operate or permit to sell or rent, the Air Pollution Control Officer shall notify the applicant in writing of the reasons therefor. Service of this notification may be made in person or by mail, and such service may be proved by the written acknowledgment of the persons served or affidavit of the person making the service. The Air Pollution Control Officer shall not accept a further application unless the applicant has complied with the objections specified by the Air Pollution Control Officer as his reasons for denial of the authority to construct, the permit to operate or the permit to sell or rent.

RULE 23. (Amended 1-16-58) FURTHER INFORMATION

Before acting on an application for authority to construct, permit to operate or permit to sell or rent, the Air Pollution Control Officer may require the applicant to furnish further information or further plans or specifications.

RULE 24. (Amended 1-16-58) APPLICATIONS DEEMED DENIED

The applicant may at his option deem the authority to construct, permit to operate or permit to sell or rent denied if the Air Pollution Control Officer fails to act on the application within 30 days after filing, or within 30 days after applicant furnishes the further information, plans and specifications requested by the Air Pollution Control Officer, whichever is later.

RULE 25. (Amended 1-16-58) APPEALS

Within 10 days after notice, by the Air Pollution Control Officer, of denial or conditional approval of an authority to construct, permit to operate or permit to sell or rent, the applicant may petition the Hearing Board, in writing, for a public hearing. The Hearing Board, after notice and a public hearing held within 30 days after filing the petition, may sustain or reverse the action of the Air Pollution Control Officer; such order may be made subject to specified conditions.

REGULATION III. FEES

RULE 40. PERMIT FEES

Every applicant, except any state or local governmental agency or public district, for an authority to construct or a permit to operate any article, machine, equipment or other contrivance, for which an authority to construct or permit to operate is required by the State law or the Rules and Regulations of the Air Pollution Control District, shall pay a filing fee of $40.00. Where an application is filed for a permit to operate any article, machine, equipment or other contrivance by reason of transfer from one person to another, and where a permit to operate had previously been granted under Rule 10 and no alteration, addition or trans-

fer of location has been made, the applicant shall pay only a $10.00 filing fee.

(Amended 6-1-65) Every applicant, except any state or local governmental agency or public district, for a permit to operate, who files an application with the Air Pollution Control Officer, shall, in addition to the filing fee prescribed herein, pay the fee for the issuance of a permit to operate in the amount prescribed in the following schedules, provided, however, that the filing fee shall be applied to the fee prescribed for the issuance of the permit to operate.

(Amended 6-1-65) If an application for an authority to construct or a permit to operate is canceled, or if an authority to construct or a permit to operate is denied and such denial becomes final, the filing fee required herein shall not be refunded nor applied to any subsequent application.

(Amended 6-1-65) Where an application is filed for a permit to operate any article, machine, equipment or other contrivance by reason of transfer of location or transfer from one person to another, or both, and where a permit to operate had previously been granted for such equipment under Rule 10 and an alteration or addition has been made, the applicant shall be assessed a fee based upon the increase in total horsepower rating, the increase in total fuel consumption expressed in thousands of British Thermal Units (BTU) per hour, the increase in total electrical energy rating, the increase in maximum horizontal inside cross sectional area or the increase in total stationary container capacity resulting from such alterations or additions, as described in the fee schedules contained herein. Where the application is for transfer of location and no alteration or addition has been made, the applicant shall pay only a filing fee of $40.

(Amended 6-1-65) Where an application is filed for an authority to construct or a permit to operate exclusively involving revisions to the conditions of an existing permit to operate or involving alterations or additions resulting in a change to any existing article, machine, equipment or other contrivance holding a permit under the provisions of Rule 10 of these Rules and Regulations, the applicant shall be assessed a fee based upon the increase in total horsepower rating, the increase in total fuel consumption expressed in thousands of British Thermal Units (BTU) per hour, the increase in total electrical energy rating, the increase in maximum horizontal inside cross sectional area or the increase in total stationary container capacity resulting from such alterations or additions, as described in the fee schedules contained herein. Where there is no change or is a decrease in such ratings, the applicant shall pay only the amount of the filing fee required herein.

After the provisions for granting permits as set forth in Chapter 2, Division 20, of the Health and Safety Code and the Rules and Regulations have been complied with, the applicant shall be notified by the Air Pollution Control Officer, in writing, of the fee to be paid for issuance of the permit to operate. Such notice may be given by personal service or by deposit, postpaid, in the United States mail and shall serve as a temporary permit to operate for 30 days from the date of personal service or mailing. Nonpayment of the fee within this period of time shall result in the automatic cancellation of the application.

In the event that more than one fee schedule is applicable to a permit to operate, the governing schedule shall be that which results in the higher fee.

(Adopted 6-1-65) Where a single permit to operate has been granted under Rule 10 prior to July 1, 1957, and where the Air Pollution Control Officer would, since that date, have issued separate or revised permits for each permit unit included in the original application, the Air Pollution Control Officer may issue such separate or revised permits without fees.

In the event that a permit to operate is granted by the Hearing Board after denial by the Air Pollution Control Officer or after the applicant deems his application denied, the applicant shall pay the fee prescribed in the following schedules within 30 days after the date of the decision of the Hearing Board. Nonpayment of the fee within this period of time shall result in automatic cancellation of the permit and the application. Such a fee shall not be charged for a permit to operate granted by the Hearing Board for the duration of a variance.

(Amended 7-1-64) A request for a duplicate permit to operate shall be made in writing to the Air Pollution Control Officer within 10 days after the destruction, loss or defacement of a permit to operate. A fee of $2.00 shall be charged, except to any state or local governmental agency or public district, for issuing a duplicate permit to operate.

It is hereby determined that the cost of issuing permits and of inspections pertaining to such issuance exceeds the fees prescribed.

Schedule 1 (Amended 7-1-64)

ELECTRIC MOTOR HORSEPOWER SCHEDULE

Any article, machine, equipment, or other contrivance where an electric motor is used as the power supply shall be assessed a permit fee based on the total rated motor horsepower of all electric

motors included in any article, machine, equipment or other contrivance, in accordance with the following schedule:

	Horsepower	Fee
a)	up to and including 2-1/2	$ 40.00
b)	greater than 2-1/2 but less than 5	100.00
c)	5 or greater but less than 15	200.00
d)	15 or greater but less than 45	300.00
e)	45 or greater but less than 65	400.00
f)	65 or greater but less than 125	500.00
g)	125 or greater but less than 200	600.00
h)	200 or greater	800.00

Schedule 2 (Amended 7-1-64)

FUEL BURNING EQUIPMENT SCHEDULE

Any article, machine, equipment or other contrivance in which fuel is burned, with the exception of incinerators which are covered in Schedule 4, shall be assessed a permit fee based upon the design fuel consumption of the article, machine, equipment or other contrivance expressed in thousands of British thermal units (BTU) per hour, using gross heating values of the fuel, in accordance with the following schedule:

	1000 British Thermal Units per Hour	Fee
a)	up to and including 150	$ 40.00
b)	greater than 150 but less than 400	100.00
c)	400 or greater but less than 650	200.00
d)	650 or greater but less than 1500	300.00
e)	1500 or greater but less than 2500	400.00
f)	2500 or greater but less than 5000	500.00
g)	5000 or greater but less than 15000	600.00
h)	15000 or greater	800.00

Schedule 3 (Amended 7-1-64)

ELECTRICAL ENERGY SCHEDULE

Any article, machine, equipment or other contrivance which uses electrical energy, with the exception of electric motors covered in Schedule 1, shall be assessed a permit fee based on the total kilovolt ampere (KVA) ratings, in accordance with the following schedule:

	Kilovolt Amperes	Fee
a)	up to and including 20	$ 40.00
b)	greater than 20 but less than 40	100.00
c)	40 or greater but less than 145	200.00
d)	145 or greater but less than 450	300.00
e)	450 or greater but less than 4500	400.00
f)	4500 or greater but less than 14500	500.00
g)	14500 or greater but less than 45000	600.00
h)	45000 or greater	800.00

Schedule 4 (Amended 7-1-64)

INCINERATOR SCHEDULE

Any article, machine, equipment or other contrivance designed and used primarily to dispose of combustible refuse by wholly consuming the material charged leaving only the ashes or residue shall be assessed a permit fee based on the following schedule of the maximum horizontal inside cross sectional area, in square feet, of the primary combustion chamber:

	Area, in Square Feet	Fee
a)	up to and including 3	$ 40.00
b)	greater than 3 but less than 4	100.00
c)	4 or greater but less than 7	200.00
d)	7 or greater but less than 10	300.00
e)	10 or greater but less than 15	400.00
f)	15 or greater but less than 23	500.00
g)	23 or greater but less than 40	600.00
h)	40 or greater	800.00

Schedule 5 (Amended 7-1-64)

STATIONARY CONTAINER SCHEDULE

Any stationary tank, reservoir, or other container shall be assessed a permit fee based on the following schedule of capacities in gallons or cubic equivalent:

	Gallons	Fee
a)	up to and including 4000	$ 40.00
b)	greater than 4000 but less than 10000	60.00
c)	10000 or greater but less than 40000	100.00
d)	40000 or greater but less than 100000	200.00
e)	100000 or greater but less than 400000	300.00
f)	400000 or greater but less than 1000000	400.00
g)	1000000 or greater but less than 4000000	500.00
h)	4000000 or greater	600.00

Schedule 6 (Amended 7-1-64)

MISCELLANEOUS SCHEDULE

Any article, machine, equipment or other contrivance which is not included in the preceding schedules shall be assessed a permit fee of $40.00.

RULE 42. (Amended 3-14-63) HEARING BOARD FEES

a. Every applicant or petitioner for variance, or for the extension, revocation or modification of a variance, or for an appeal from a denial or conditional approval of an authority to construct, permit to operate or permit to sell or rent, except any state or local governmental agency or public district, shall pay to the Clerk of the Hearing Board, on filing, a fee in the sum of $16.50. It is hereby determined that the cost of administration of Article 5, Chapter 2, Division 20, Health and Safety Code, or Rule 25 of these Rules and Regulations, exceeds $16.50 per petition.

b. (Amended 3-14-63) Any person requesting a transcript of the hearing shall pay the cost of such transcript.

c. This rule shall not apply to petitions filed by the Air Pollution Control Officer.

RULE 43. ANALYSIS FEES

Whenever the Air Pollution Control Officer finds that an analysis of the emission from any source is necessary to determine the extent and amount of pollutants being discharged into the atmosphere which cannot be determined by visual observation, he may order the collection of samples and the analysis made by qualified personnel of the Air Pollution Control District. The time required for collecting samples, making the analysis and preparing the necessary reports, but excluding time required in going to and from such premises shall be charged against the owner or operator of said premises in a reasonable sum to be determined by the Air Pollution Control Officer, which said sum is not to exceed the actual cost of such work.

RULE 44. TECHNICAL REPORTS - CHARGES FOR:

Information, circulars, reports of technical work, and other reports prepared by the Air Pollution Control District when supplied to other governmental agencies or individuals or groups requesting copies of the same may be charged for by the District in a sum not to exceed the cost of preparation and distribution of such documents. All such monies collected shall be turned into the general funds of the said District.

REGULATION IV. PROHIBITIONS

RULE 50. RINGELMANN CHART

A person shall not discharge into the atmosphere from any single source of emission whatsoever any air contaminant for a period or periods aggregating more than three minutes in any one hour which is:

a. As dark or darker in shade as that designated as No. 2 on the Ringelmann Chart, as published by the United States Bureau of Mines, or

b. Of such opacity as to obscure an observer's view to a degree equal to or greater than does smoke described in subsection (a) of this Rule.

RULE 51. NUISANCE

A person shall not discharge from any source whatsoever such quantities of air contaminants or other material which cause injury, detriment, nuisance or annoyance to any considerable number of persons or to the public or which endanger the comfort, repose, health or safety of any such persons or the public or which cause or have a natural tendency to cause injury or damage to business or property.

RULE 52. (Amended 3-2-67) PARTICULATE MATTER

Except as otherwise provided in Rules 53 and 54, a person shall not discharge into the atmosphere from any source particulate matter in excess of 0.3 grain per cubic foot of gas at standard conditions.

RULE 53. (Amended 1-16-58) SPECIFIC CONTAMINANTS

A person shall not discharge into the atmosphere from any single source of emission whatsoever any one or more of the following contaminants, in any state or combination thereof, exceeding in concentration at the point of discharge:

a. Sulphur Compounds calculated as sulphur dioxide (SO_2): 0.2 per cent, by volume.

b. (Amended 1-16-58) Combustion Contaminants: 0.3 grain per cubic foot of gas calculated to 12 per cent of carbon dioxide (CO_2) at standard conditions. In measuring the combustion contaminants from incinerators used to dispose of combustible refuse by burning, the carbon dioxide (CO_2) produced by combustion of any liquid or gaseous fuels shall be excluded from the calculation to 12 per cent of carbon dioxide (CO_2).

RULE 53.1. SCAVENGER PLANTS

Where a separate source of air pollution is a scavenger or recovery plant, recovering pollutants which would otherwise be emitted to the atmosphere,

the Air Pollution Control Officer may grant a permit to operate where the total emission of pollutants is substantially less with the plant in operation than when closed, even though the concentration exceeds that permitted by Rule 53 (a). The Air Pollution Control Officer shall report immediately in writing to the Air Pollution Control Board the granting of any such permit, together with the facts and reasons therefor.

RULE 54. DUST AND FUMES

A person shall not discharge in any one hour from any source whatsoever dust or fumes in total quantities in excess of the amount shown in the following table: (see next page)

To use the following table, take the process weight per hour as such is defined in Rule 2(j). Then find this figure on the table, opposite which is the maximum number of pounds of contaminants which may be discharged into the atmosphere in any one hour. As an example, if A has a process which emits contaminants into the atmosphere and which process takes 3 hours to complete, he will divide the weight of all materials in the specific process, in this example, 1,500 lbs. by 3 giving a process weight per hour of 500 lbs. The table shows that A may not discharge more than 1.77 lbs. in any one hour during the process. Where the process weight per hour falls between figures in the left hand column, the exact weight of permitted discharge may be interpolated.

RULE 55. (Amended 1-16-58) EXCEPTIONS

The provisions of Rule 50 do not apply to:

a. Smoke from fires set by or permitted by any public officer if such fire is set or permission given in the performance of the official duty of such officer, and such fire in the opinion of such officer is necessary:

   (1) For the purpose of the prevention of a fire hazard which cannot be abated by any other means, or

   (2) The instruction of public employees in the methods of fighting fire.

b. Smoke from fires set pursuant to permit on property used for industrial purposes for the purpose of instruction of employees in methods of fighting fire.

c. Agricultural operations in the growing of crops, or raising of fowls or animals.

d. The use of an orchard or citrus grove heater which does not produce unconsumed solid carbonaceous matter at a rate in excess of one (1) gram per minute.

e. The use of other equipment in agricultural operations in the growing crops, or raising of fowls or animals.

RULE 56. (Amended 1-16-58) STORAGE OF PETROLEUM PRODUCTS

A person shall not place, store or hold in any stationary tank, reservoir or other container of more than 40,000 gallons capacity any gasoline or any petroleum distillate having a vapor pressure of 1.5 pounds per square inch absolute or greater under actual storage conditions, unless such tank, reservoir or other container is a pressure tank maintaining working pressures sufficient at all times to prevent hydrocarbon vapor or gas loss to the atmosphere, or is designed and equipped with one of the following vapor loss control devices, properly installed, in good working order and in operation:

a. A floating roof, consisting of a pontoon type or double-deck type roof, resting on the surface of the liquid contents and equipped with a closure seal, or seals, to close the space between the roof edge and tank wall. The control equipment provided for in this paragraph shall not be used if the gasoline or petroleum distillate has a vapor pressure of 11.0 pounds per square inch absolute or greater under actual storage conditions. All tank gauging and sampling devices shall be gas-tight except when gauging or sampling is taking place.

b. A vapor recovery system, consisting of a vapor gathering system capable of collecting the hydrocarbon vapors and gases discharged and a vapor disposal system capable of processing such hydrocarbon vapors and gases so as to prevent their emission to the atmosphere and with all tank gauging and sampling devices gas-tight except when gauging or sampling is taking place.

c. Other equipment of equal efficiency, provided such equipment is submitted to and approved by the Air Pollution Control Officer.

RULE 57. (Amended 1-16-58) OPEN FIRES

A person shall not burn any combustible refuse in any open outdoor fire within the Los Angeles Basin, except:

a. When such fire is set or permission for such fire is given in the performance of the official

TABLE

*Process Wt/hr(lbs)	Maximum Weight Disch/hr(lbs)	*Process Wt/hr(lbs)	Maximum Weight Disch/hr(lbs)
50	.24	3400	5.44
100	.46	3500	5.52
150	.66	3600	5.61
200	.85	3700	5.69
250	1.03	3800	5.77
300	1.20	3900	5.85
350	1.35	4000	5.93
400	1.50	4100	6.01
450	1.63	4200	6.08
500	1.77	4300	6.15
550	1.89	4400	6.22
600	2.01	4500	6.30
650	2.12	4600	6.37
700	2.24	4700	6.45
750	2.34	4800	6.52
800	2.43	4900	6.60
850	2.53	5000	6.67
900	2.62	5500	7.03
950	2.72	6000	7.37
1000	2.80	6500	7.71
1100	2.97	7000	8.05
1200	3.12	7500	8.39
1300	3.26	8000	8.71
1400	3.40	8500	9.03
1500	3.54	9000	9.36
1600	3.66	9500	9.67
1700	3.79	10000	10.0
1800	3.91	11000	10.63
1900	4.03	12000	11.28
2000	4.14	13000	11.89
2100	4.24	14000	12.50
2200	4.34	15000	13.13
2300	4.44	16000	13.74
2400	4.55	17000	14.36
2500	4.64	18000	14.97
2600	4.74	19000	15.58
2700	4.84	20000	16.19
2800	4.92	30000	22.22
2900	5.02	40000	28.3
3000	5.10	50000	34.3
3100	5.18	60000 or more	40.0
3200	5.27		
3300	5.36		

*See Definition in Rule 2(j).

duty of any public officer, and such fire in the opinion of such officer is necessary:

1. For the purpose of the prevention of a fire hazard which cannot be abated by any other means, or

2. The instruction of public employees in the methods of fighting fire.

b. When such fire is set pursuant to permit on property used for industrial purposes for the purpose of instruction of employees in methods of fighting fire.

c. When such fire is set in the course of any agricultural operation in the growing of crops, or raising of fowls or animals.

These exceptions shall not be effective on any calendar day on which the Air Pollution Control Officer determines that:

1. The inversion base at 4:00 A.M., Pacific Standard Time, will be lower than one thousand five hundred feet above mean sea level, and

2. The maximum mixing height will not be above three thousand five hundred feet, and

3. The average surface wind speed between 6:00 A.M. and 12:00 noon, Pacific Standard Time, will not exceed five miles per hour.

RULE 58. (Amended 3-14-63) INCINERATOR BURNING

A person shall not burn any combustible refuse in any incinerator within the Los Angeles Basin except in a multiple-chamber incinerator as described in Rule 2(p), or in equipment found by the Air Pollution Control Officer in advance of such use to be equally effective for the purpose of air pollution control as an approved multiple-chamber incinerator.

RULE 59. (Amended 1-16-58) OIL-EFFLUENT WATER SEPARATOR

A person shall not use any compartment of any single or multiple compartment oil-effluent water separator which compartment receives effluent water containing 200 gallons a day or more of any petroleum product or mixture of petroleum products from any equipment processing, refining, treating, storing or handling kerosine or other petroleum product of equal or greater volatility than kerosine, unless such compartment is equipped with one of the following vapor loss control devices, properly installed, in good working order and in operation:

a. A solid cover with all openings sealed and totally enclosing the liquid contents. All gauging and sampling devices shall be gas-tight except when gauging or sampling is taking place.

b. A floating roof, consisting of a pontoon type or double-deck type roof, resting on the surface of the liquid contents and equipped with a closure seal, or seals, to close the space between the roof edge and container wall. All gauging and sampling devices shall be gas-tight except when gauging or sampling is taking place.

c. A vapor recovery system, consisting of a vapor gathering system capable of collecting the hydrocarbon vapors and gases discharged and a vapor disposal system capable of processing such hydrocarbon vapors and gases so as to prevent their emission to the atmosphere and with all tank gauging and sampling devices gas-tight except when gauging or sampling is taking place.

d. Other equipment of equal efficiency, provided such equipment is submitted to and approved by the Air Pollution Control Officer.

This rule shall not apply to any oil-effluent water separator used exclusively in conjunction with the production of crude oil.

For the purpose of this rule, "kerosine" is defined as any petroleum product which, when distilled by ASTM standard test Method D 86-56, will give a temperature of 401°F. or less at the 10 per cent point recovered.

RULE 60. (Adopted 12-15-55) CIRCUMVENTION

A person shall not build, erect, install, or use any article, machine, equipment or other contrivance, the use of which, without resulting in a reduction in the total release of air contaminants to the atmosphere, reduces or conceals an emission which would otherwise constitute a violation of Division 20, Chapter 2 of the Health and Safety Code of the State of California or of these Rules and Regulations. This Rule shall not apply to cases in which the only violation involved is of Section 24243 of the Health and Safety Code of the State of California, or of Rule 51 of these Rules and Regulations.

RULE 61. (Amended 3-14-63) GASOLINE LOADING INTO TANK TRUCKS AND TRAILERS

A person shall not load gasoline into any tank truck or trailer from any loading facility unless such loading facility is equipped with a vapor collection and disposal system or its equivalent, properly installed, in good working order and in operation.

When loading is effected through the hatches of a tank truck or trailer with a loading arm equipped with a vapor collecting adaptor, a pneumatic, hydraulic or other mechanical means shall be provided to force a vapor-tight seal between the adaptor and the hatch. A means shall be provided to prevent liquid gasoline drainage from the loading device when it is removed from the hatch of any tank truck or trailer, or to accomplish complete drainage before such removal.

When loading is effected through means other than hatches, all loading and vapor lines shall be equipped with fittings which make vapor-tight connections and which close automatically when disconnected.

The vapor disposal portion of the system shall consist of one of the following:

a. A vapor-liquid absorber system with a minimum recovery efficiency of 90 per cent by weight of all the hydrocarbon vapors and gases entering such disposal system.

b. A variable vapor space tank, compressor, and fuel gas system of sufficient capacity to receive all hydrocarbon vapors and gases displaced from the tank trucks and trailers being loaded.

c. (Amended 3-14-63) Other equipment of at least 90 per cent efficiency, provided such equipment is submitted to and approved by the Air Pollution Control Officer.

This rule shall not apply to the loading of gasoline into tank trucks and trailers from any loading facility from which not more than 20,000 gallons of gasoline are loaded in any one day.

For the purpose of this rule, any petroleum distillate having a Reid vapor pressure of four pounds or greater shall be included by the term "gasoline".

(Amended 12-4-58) For the purpose of this rule, "loading facility" means any aggregation or combination of gasoline loading equipment which is both (1) possessed by one person, and (2) located so that all the gasoline loading outlets for such aggregation or combination of loading equipment can be encompassed within any circle of 300 feet in diameter.

RULE 62. (Amended 3-16-61) SULFUR CONTENTS OF FUELS

A person shall not burn within the Los Angeles Basin at any time between May 1 and September 30, both dates inclusive, during the calendar year 1959, and each year thereafter between April 15 and November 15 both inclusive, of the same calendar year, any gaseous fuel containing sulfur compounds in excess of 50 grains per 100 cubic feet of gaseous fuel, calculated as hydrogen sulfide at standard conditions, or any liquid fuel or solid fuel having a sulfur content in excess of 0.5 per cent by weight.

The provisions of this rule shall not apply to:

a. The burning of sulfur, hydrogen sulfide, acid sludge or other sulfur compounds in the manufacturing of sulfur or sulfur compounds.

b. The incinerating of waste gases provided that the gross heating value of such gases is less than 300 British thermal units per cubic foot at standard conditions and the fuel used to incinerate such waste gases does not contain sulfur or sulfur compounds in excess of the amount specified in this rule.

c. The use of solid fuels in any metallurgical process.

d. The use of fuels where the gaseous products of combustion are used as raw materials for other processes.

e. The use of liquid or solid fuel to propel or test any vehicle, aircraft, missile, locomotive, boat or ship.

f. The use of liquid fuel whenever the supply of gaseous fuel, the burning of which is permitted by this rule, is not physically available to the user due to accident, act of God, act of war, act of the public enemy, or failure of the supplier.

RULE 62.1 (Adopted 1-14-64)

a. A person shall not burn within the Los Angeles Basin at any time between the days of November 16 of any year and April 14 of the next succeeding calendar year, both dates inclusive, any fuel described in the first paragraph of Rule 62 of these Rules and Regulations.

b. The provisions of this Rule do not apply to:

(1) Any use of fuel described in Subsections a, b, c, d, e, and f of said Rule 62 under the conditions and for the uses set forth in said Subsections.

(2) The use of liquid fuel during a period for which the supplier of gaseous fuel, the burning of which is not prohibited by this Rule, interrupts the delivery of gaseous fuel to the user.

c. Every holder of, and every applicant for a permit to operate fuel-burning equipment under these Rules and Regulations shall notify the air pollution control officer in the manner and form prescribed by him, of each interruption in and resumption of delivery of gaseous fuel to his equipment.

RULE 63. (Amended 1-25-62) GASOLINE SPECIFICATIONS

a. A person shall not, after June 30, 1960, sell or supply for use within the District as a fuel for motor vehicles as defined by the Vehicle Code of the State of California, gasoline having a degree of unsaturation greater than that indicated by a Bromine Number of 30 as determined by ASTM Method D1159-57T modified by omission of the mercuric chloride catalyst.

b. For the purpose of this rule, the term "gasoline" means any petroleum distillate having a Reid vapor pressure of more than four pounds.

RULE 64. (Amended 3-2-67) REDUCTION OF ANIMAL MATTER

A person shall not operate or use any article, machine, equipment or other contrivance for the reduction of animal matter unless all gases, vapors and gas-entrained effluents from such an article, machine, equipment or other contrivance are:

a. Incinerated at temperatures of not less than 1200 degrees Fahrenheit for a period of not less than 0.3 second, or

b. Processed in such a manner determined by the Air Pollution Control Officer to be equally, or more, effective for the purpose of air pollution control than (a) above.

A person incinerating or processing gases, vapors or gas-entrained effluents pursuant to this rule shall provide, properly install and maintain in calibration, in good working order and in operation devices, as specified in the Authority to Construct or Permit to Operate or as specified by the Air Pollution Control Officer, for indicating temperature, pressure or other operating conditions.

For the purpose of this rule, "reduction" is defined as any heated process, including rendering, cooking, drying, dehydrating, digesting, evaporating and protein concentrating.

The provisions of this rule shall not apply to any article, machine, equipment or other contrivance used exclusively for the processing of food for human consumption.

RULE 65. (Amended 6-1-65) GASOLINE LOADING INTO TANKS

A person shall not after January 1, 1965, load or permit the loading of gasoline into any stationary tank with a capacity of 250 gallons or more from any tank truck or trailer, except through a permanent submerged fill pipe, unless such tank is equipped with a vapor loss control device as described in Rule 56, or is a pressure tank as described in Rule 56.

The provisions of the first paragraph of this rule shall not apply to the loading of gasoline into any tank having a capacity of less than 2,000 gallons which was installed prior to the date of adoption of this rule nor to any underground tank installed prior to the date of adoption of this rule where the fill line between the fill connection and tank is offset.

Any person operating or using any gasoline tank with a capacity of 250 gallons or more installed prior to the date of adoption of this rule shall apply for a permit to operate such tank before January 1, 1965. The provisions of Rule 40 shall not apply during the period between the date of adoption of this rule and January 1, 1965, to any gasoline tank installed prior to the date of adoption of this rule provided an application for permit to operate is filed before January 1, 1965.

A person shall not install any gasoline tank with a capacity of 250 gallons or more unless such tank is equipped as described in the first paragraph of this rule.

For the purpose of this rule, the term "gasoline" is defined as any petroleum distillate having a Reid vapor pressure of 4 pounds or greater.

For the purpose of this rule, the term "submerged fill pipe" is defined as any fill pipe the discharge opening of which is entirely submerged when the liquid level is 6 inches above the bottom of the tank. "Submerged fill pipe" when applied to a tank which is loaded from the side is defined as any fill pipe the discharge opening of which is entirely submerged when the liquid level is 18 inches above the bottom of the tank.

(Adopted 6-1-65) The provisions of this rule do not apply to any stationary tank which is used primarily for the fueling of implements of husbandry, as such vehicles are defined in Division 16 (Section 36000, et seq.) of the Vehicle Code.

RULE 66. (Adopted 7-28-66) ORGANIC SOLVENTS

a. A person shall not discharge more than 15 pounds of organic materials into the atmosphere in any one day from any article, machine, equipment or other contrivance in which

any organic solvent or any material containing organic solvent comes into contact with flame or is baked, heat-cured or heat-polymerized, in the presence of oxygen, unless all organic materials discharged from such article, machine, equipment or other contrivance have been reduced either by at least 85 per cent overall or to not more than 15 pounds in any one day.

b. A person shall not discharge more than 40 pounds of organic material into the atmosphere in any one day from any article, machine, equipment or other contrivance used under conditions other than described in section (a), for employing, applying, evaporating or drying any photochemically reactive solvent, as defined in section (k), or material containing such solvent, unless all organic materials discharged from such article, machine, equipment or other contrivance have been reduced either by at least 85 per cent overall or to not more than 40 pounds in any one day.

c. Any series of articles, machines, equipment or other contrivances designed for processing a continuously moving sheet, web, strip or wire which is subjected to any combination of operations described in sections (a) or (b) involving any photochemically reactive solvent, as defined in section (k), or material containing such solvent, shall be subject to compliance with section (b). Where only non-photochemically reactive solvents or material containing only non-photochemically reactive solvents are employed or applied, and where any portion or portions of said series of articles, machines, equipment or other contrivances involves operations described in section (a), said portions shall be collectively subject to compliance with section (a).

d. Emissions of organic materials to the atmosphere from the clean-up with photochemically reactive solvent, as defined in section (k), of any article, machine, equipment or other contrivance described in sections (a), (b) or (c), shall be included with the other emissions of organic materials from that article, machine, equipment or other contrivance for determining compliance with this rule.

e. Emissions of organic materials to the atmosphere as a result of spontaneously continuing drying of products for the first 12 hours after their removal from any article, machine, equipment or other contrivance described in sections (a), (b) or (c), shall be included with other emissions of organic materials from that article, machine, equipment or other contrivance for determining compliance with this rule.

f. Emissions of organic materials into the atmosphere required to be controlled by sections (a), (b) or (c), shall be reduced by:

(1) Incineration, provided that 90 per cent or more of the carbon in the organic material being incinerated is oxidized to carbon dioxide, or

(2) Adsorption, or

(3) Processing in a manner determined by the Air Pollution Control Officer to be not less effective than (1) or (2) above.

g. A person incinerating, adsorbing, or otherwise processing organic materials pursuant to this rule shall provide, properly install and maintain in calibration, in good working order and in operation, devices as specified in the authority to construct or the permit to operate, or as specified by the Air Pollution Control Officer, for indicating temperatures, pressures, rates of flow or other operating conditions necessary to determine the degree and effectiveness of air pollution control.

h. Any person using organic solvents or any materials containing organic solvents shall supply the Air Pollution Control Officer, upon request and in the manner and form prescribed by him, written evidence of the chemical composition, physical properties and amount consumed for each organic solvent used.

i. The provisions of this rule shall not apply to:

(1) The manufacture of organic solvents, or the transport or storage of organic solvents or materials containing organic solvents.

(2) The use of equipment for which other requirements arespecified by Rules 56, 59, 61 or 65 or which are exempt from air pollution control requirements by said rules.

(3) The spraying or other employment of insecticides, pesticides or herbicides.

(4) The employment, application, evaporation or drying of saturated halogenated hydrocarbons or perchloroethylene.

j. For the purposes of this rule, organic solvents include diluents and thinners and are defined as organic materials which are liquids at standard conditions and which are used as dissolvers, viscosity reducers or cleaning agents.

k. For the purposes of this rule, a photochemically reactive solvent is any solvent with an aggregate of more than 20 per cent of its total volume composed of the chemical compounds classified below or which exceeds any of the following individual percentage composition limitations, referred to the total volume of solvent:

(1) A combination of hydrocarbons, alcohols, aldehydes, esters, ethers or ketones having an olefinic or cycloolefinic type of unsaturation: 5 per cent;

(2) A combination of aromatic compounds with eight or more carbon atoms to the molecule except ethylbenzene: 8 per cent;

(3) A combination of ethylbenzene, ketones having branched hydrocarbon structures, trichloroethylene or toluene: 20 per cent.

Whenever any organic solvent or any constituent of an organic solvent may be classified from its chemical structure into more than one of the above groups of organic compounds, it shall be considered as a member of the most reactive chemical group, that is, that group having the least allowable per cent of the total volume of solvents.

l. For the purposes of this rule, organic materials are defined as chemical compounds of carbon excluding carbon monoxide, carbon dioxide, carbonic acid, metallic carbides, metallic carbonates and ammonium carbonate.

m. This rule shall be effective on the date of its adoption as to any article, machine, equipment or other contrivance, not then completed and put into service. As to all other articles, machines, equipment or other contrivances, this rule shall be effective:

(1) On July 1, 1967, for those emitting 500 pounds or more of organic materials in any one day.

(2) On October 1, 1967, for those emitting 100 pounds or more but less than 500 pounds of organic materials in any one day.

(3) On March 1, 1968, for those subject to compliance with section (a), and emitting 15 pounds or more but less than 100 pounds of organic materials in any one day, and for those subject to compliance with section (b), and emitting 40 pounds or more but less than 100 pounds in any one day.

RULE 66.1 (Adopted 7-28-66) ARCHITECTURAL COATINGS

a. After July 1, 1967, a person shall not sell or offer for sale for use in Los Angeles County, in containers of one quart capacity or larger, any architectural coating containing photochemically reactive solvent, as defined in Rule 66(k).

b. After July 1, 1967, a person shall not employ, apply, evaporate or dry in Los Angeles County any architectural coating, purchased in containers of one quart capacity or larger, containing photochemically reactive solvent, as defined in Rule 66(k).

c. After July 1, 1967, a person shall not thin or dilute any architectural coating with a photochemically reactive solvent, as defined in Rule 66(k).

d. For the purposes of this rule, an architectural coating is defined as a coating used for residential or commercial buildings and their appurtenances; or industrial buildings.

RULE 66.2 (Adopted 7-28-66) DISPOSAL AND EVAPORATION OF SOLVENTS

A person shall not during any one day dispose of a total of more than 1-1/2 gallons of any photochemically reactive solvent, as defined in Rule 66(k), or of any material containing more than 1-1/2 gallons of any such photochemically reactive solvent by any means which will permit the evaporation of such solvent into the atmosphere.

REGULATION V. PROCEDURE BEFORE THE HEARING BOARD

RULE 75. GENERAL

This regulation shall apply to all hearings before the Hearing Board of the Air Pollution Control District.

RULE 76. (Revised 8-25-64) FILING PETITIONS

Requests for hearing shall be initiated by the filing of a petition in triplicate with the Clerk of the Hearing Board at Room 601B, 220 North Broadway, Los Angeles, California, 90012, and the payment of the fee of $16.50 provided for in Rule 42 of these Rules and Regulations, after service of a copy of the petition has been made on the Air Pollution Control Officer at 434 South San Pedro Street, Los Angeles, California, 90013, and one copy on the holder of the permit or variance, if any, involved. Service may be made in person or by mail, and service may be proved by written acknowledgment

of the person served or by the affidavit of the person making the service.

RULE 77. (Amended 1-16-58) CONTENTS OF PETITIONS

Every petition shall state:

a. The name, address and telephone number of the petitioner, or other person authorized to receive service of notices.

b. Whether the petitioner is an individual, copartnership, corporation or other entity, and names and address of the partners if a copartnership, names and address of the officers, if a corporation, and the names and address of the persons in control, if other entity.

c. The type of business or activity involved in the application and the street address at which it is conducted.

d. A brief description of the article, machine, equipment or other contrivance, if any, involved in the application.

e. The section or rule under which the petition is filed; that is, whether petitioner desires a hearing:

(1) to determine whether a permit shall be revoked or suspended permit reinstated under Section 24274, Health and Safety Code of the State of California;

(2) for a variance under Section 24292, Health and Safety Code;

(3) to revoke or modify a variance under Section 24298, Health and Safety Code;

(4) (Amended 1-16-68) to review the denial or conditional granting of an authority to construct, permit to operate or permit to sell or rent under Rule 25 of these Rules and Regulations.

f. Each petition shall be signed by the petitioner, or by some person on his behalf, and where the person signing is not the petitioner it shall set forth his authority to sign.

g. Petitions for revocation of permits shall allege in addition the rule under which permit was granted, the rule or section which is alleged to have been violated, together with a brief statement of the facts constituting such alleged violation.

h. Petitions for reinstatement of suspended permits shall allege in addition the rule under which the permit was granted, the request and alleged refusal which formed the basis for such suspension, together with a brief statement as to why information requested, if any, was not furnished, whether such information is believed by petitioner to be pertinent, and, if so, when it will be furnished.

i. All petitions shall be typewritten, double spaced, on legal or letter size paper, on one side of the paper only, leaving a margin of at least one inch at the top and left side of each sheet.

RULE 78. (Amended 4-2-64). PETITIONS FOR VARIANCES

In addition to the matters required by Rule 77, petitions for variances shall state briefly:

a. The section, rule or order complained of.

b. The facts showing why compliance with the section, rule, or order is unreasonable.

c. For what period of time the variance is sought and why

d. The damage or harm resulting or which would result to petitioner from a compliance with such section, rule or order.

e. The requirements which petitioner can meet and the date when petitioner can comply with such requirements.

f. The advantages and disadvantages to the residents of the district resulting from requiring compliance or resulting from granting a variance.

g. Whether or not operations under such variance, if granted, would constitute a ruisance.

h. Whether or not any case involving the same identical equipment or process is pending in any court, civil or criminal.

i. (Amended 4-2-64) Whether or not the subject equipment or process is covered by a permit to operate issued by the Air Pollution Control Officer.

RULE 79. (Amended 1-16-58) APPEAL FROM DENIAL

A petition to review a denial or conditional approval of an authority to construct, permit to operate or permit to sell or rent shall, in addition to the mat-

ters required by Rule 77, set forth a summary of the application or a copy thereof and the alleged reasons for the denial or conditional approval and the reasons for appeal.

RULE 80. FAILURE TO COMPLY WITH RULES

The Clerk of the Hearing Board shall not accept for filing any petition which does not comply with these Rules relating to the form, filing and service of petitions unless the chairman or any two members of the Hearing Board direct otherwise and confirm such direction in writing. Such direction need not be made at a meeting of the Hearing Board. The chairman or any two members, without a meeting, may require the petitioner to state further facts or reframe a petition so as to disclose clearly the issues involved.

RULE 82. ANSWERS

Any person may file an answer within 10 days after service. All answers shall be served the same as petitions under Rule 76.

RULE 83. DISMISSAL OF PETITION

The petitioner may dismiss his petition at any time before submission of the case to the Hearing Board, without a hearing or meeting of the Hearing Board. The Clerk of the Hearing Board shall notify all interested persons of such dismissal.

RULE 84. (Revised 8-25-64) PLACE OF HEARING

All hearings shall be held at Room 601B, 220 North Broadway, Los Angeles, California, 90012, unless some other place is designated by the Hearing Board.

RULE 85. NOTICE OF HEARING

The Clerk of the Hearing Board shall mail or deliver a notice of hearing to the petitioner, the Air Pollution Control Officer, the holder of the permit or variance involved, if any, and to any person entitled to notice under Sections 24275, 24295 or 24299, Health and Safety Code.

RULE 86. EVIDENCE

(a) Oral evidence shall be taken only on oath or affirmation.

(b) Each party shall have these rights: to call and examine witnesses; to introduce exhibits; to cross-examine opposing witnesses on any matter relevant to the issues even though that matter was not covered in the direct examination; to impeach any witness regardless of which party first called him to testify; and to rebut the evidence against him. If respondent does not testify in his own behalf he may be called and examined as if under cross-examination.

(c) The hearing need not be conducted according to technical rules relating to evidence and witnesses. Any relevant evidence shall be admitted if it is the sort of evidence on which responsible persons are accustomed to rely in the conduct of serious affairs, regardless of the existence of any common law or statutory rule which might make improper the admission of such evidence over objection in civil actions. Hearsay evidence may be used for the purpose of supplementing or explaining any direct evidence but shall not be sufficient in itself to support a finding unless it would be admissible over objection in civil actions. The rules of privilege shall be effective to the same extent that they are now or hereafter may be recognized in civil actions, and irrelevant and unduly repetitious evidence shall be excluded.

RULE 87. PRELIMINARY MATTERS

Preliminary matters such as setting a date for hearing, granting continuances, approving petitions for filing, allowing amendments and other preliminary rulings not determinative of the merits of the case may be made by the chairman or any two members of the Hearing Board without a hearing or meeting of the Hearing Board and without notice.

RULE 88. OFFICIAL NOTICE

The Hearing Board may take official notice of any matter which may be judicially noticed by the courts of this State.

RULE 89. CONTINUANCES

The chairman or any two members of the Hearing Board shall grant any continuance of 15 days or less, concurred in by petitioner, the Air Pollution Control Officer and by every person who has filed an answer in the action and may grant any reasonable continuance; in either case such action may be ex parte, without a meeting of the Hearing Board and without prior notice.

RULE 90. DECISION

The decision shall be in writing, served and filed within 15 days after submission of the cause by the parties thereto and shall contain a brief statement of facts found to be true, the determination of the issues presented and the order of the Hearing Board. A copy shall be mailed or delivered to the Air Pollution Control Officer, the petitioner and to every person who has filed an answer or who has appeared as a party in person or by counsel at the hearing.

RULE 91. EFFECTIVE DATE OF DECISION

The decision shall become effective 15 days after delivering or mailing a copy of the decision, as provided in Rule 90, or the Hearing Board may order that the decision shall become effective sooner.

RULE 95. LACK OF PERMIT

The Hearing Board shall not receive or accept a petition for a variance for the operation or use of any article, machine, equipment or other contrivance until a permit to operate has been granted or denied by the Air Pollution Control Officer; except that an appeal from a denial of a permit to operate and a petition for a variance may be filed with the Hearing Board in a single petition. A variance granted by the Hearing Board after a denial of a permit to operate by the Air Pollution Control Officer may include a permit to operate for the duration of the variance.

REGULATION VI. ORCHARD OR CITRUS GROVE HEATERS

RULE 100. DEFINITION

"Orchard or citrus grove heater" means any article, machine, equipment or other contrivance, burning any type of fuel, capable of emitting air contaminants, used or capable of being used for the purpose of giving protection from frost damage.

RULE 101. (Amended 3-2-67) EXCEPTIONS

Rules 10, 14, 20, 21, 24, 40, 62 and 62.1 do not apply to orchard or citrus grove heaters.

RULE 102. (Amended 1-16-58) PERMITS REQUIRED

Any person erecting, altering, replacing, operating or using any orchard or citrus grove heater shall first obtain a permit from the Air Pollution Control Officer to do so.

RULE 103. (Amended 1-16-58) TRANSFER

A permit to operate shall not be transferable, whether by operation of law or otherwise, either from one location to another, from one piece of equipment to another, or from one person to another.

RULE 105. (Amended 1-16-58) APPLICATION FOR PERMITS

Every application for a permit required under Rule 102 shall be filed in the manner and form required by the Air Pollution Control Officer. Incomplete applications will not be accepted.

RULE 106. ACTION ON APPLICATIONS

The Air Pollution Control Officer shall act on all applications within a reasonable time and shall notify the applicant in writing of the approval, conditional approval or denial of the application.

RULE 107. (Amended 1-16-58) STANDARDS FOR GRANTING PERMITS

The Air Pollution Control Officer shall deny a permit if the applicant does not show that equipment described in Rules 100 and 102 is so designed or controlled that it will not produce unconsumed solid carbonaceous matter at the rate in excess of one (1) gram per minute except as prescribed under Rule 108.

RULE 108. (Amended 1-16-58) CONDITIONAL APPROVAL

a. The Air Pollution Control Officer may issue a permit subject to conditions which will bring the orchard or citrus grove heater within the standards of Rule 107 in which case the conditions shall be specified in writing.

b. Erecting, altering, operating or using under conditional permit shall be deemed acceptance of all conditions so specified.

RULE 109. (Amended 1-16-58) DENIAL OF APPLICATIONS

In the event of denial of a permit, the Air Pollution Control Officer shall notify the applicant in writing of the reasons therefor. Service of this notification may be made in person or by mail, and such service may be proved by the written acknowledgment of the person served or affidavit of the per-

son making the service. The Air Pollution Control Officer shall not accept a further application unless the applicant has complied with the objections specified by the Air Pollution Control Officer as his reasons for denial.

RULE 110. (Amended 1-16-58) APPEALS

Within 10 days after notice of denial or conditional approval of a permit by the Air Pollution Control Officer, the applicant may petition the Hearing Board, in writing, for a public hearing. The Hearing Board, after notice and a public hearing held within 30 days after filing the petition, may sustain or reverse the action of the Air Pollution Control Officer; such order may be made subject to specified conditions.

RULE 120. (Effective 1-16-58) FEES

A request for a duplicate permit for orchard or citrus grove heaters shall be made in writing to the Air Pollution Control Officer within 10 days after the destruction, loss or defacement of a permit. The fee for issuing a duplicate permit shall be $1.00.

RULE 130. (Amended 1-16-58) PROHIBITIONS

a. These rules prohibit the erecting, altering, replacing, operating or using any orchard or citrus grove heater which produces unconsumed solid carbonaceous matter at the rate of more than one (1) gram per minute, except under the conditions as set forth in Rule 108.

b. Open fires for orchard or citrus grove heating are prohibited.

c. The use of rubber tires or any rubber products in any combustion process in connection with any orchard or citrus grove heating is hereby prohibited.

d. (Amended 1-16-58) All types of orchard or citrus grove heating equipment commonly known or designated as follows:

1. Garbage pail
2. Smith Evans
3. Citrus with Olsen Stack
4. Canco 5 gallon
5. Dunn
6. Hamilton Bread Pan
7. Wheeling
8. Canco 3 gallon
9. Chinn
10. Baby Cone
11. Citrus Regular
12. Stub Stack
13. Citrus 15-inch stack
14. Exchange Model 5-1/2-inch diameter stack
15. Exchange Model 6-inch diameter stack
16. Hy-Lo Drum
17. Hy-Lo Hot Blast
18. Pheysey Beacon

may not be used or operated for the purpose of giving protection from frost damage.

e. (Amended 1-16-58) All types of orchard or citrus grove heating equipment commonly known or designated as follows:

Name	Maximum Primary Air Orifice in Square Inches
1. Hy-Lo 1929	0.606(equivalent to one hole of 7/8 in. diameter)
2. Hy-Lo 148	0.606(equivalent to one hole of 7/8 in. diameter)
3. Hy-Lo Double Stack	0.606(equivalent to one hole of 7/8 in. diameter)
4. Jumbo Cone	0.196(equivalent to one hole of 1/2 in. diameter)
5. Lemora	0.606(equivalent to one hole of 7/8 in. diameter)
6. National Double Stack	0.802(equivalent to one hole of 7/8 in. diameter and one hole of 1/2 in. diameter)
7. Surplus Chemical Warfare Service Smoke Generator	0.802(equivalent to one hole of 7/8 in. diameter and one hole of 1/2 in. diameter)

may not be used or operated for the purpose of giving protection from frost damage unless the primary air orifice(s) contain(s) not more than the maximum area designated above.

f. (Amended 1-16-58) All types of orchard or citrus grove heating equipment commonly known or designated as follows:

Name	Maximum Primary Air Orifice in Square Inches
1. Exchange Model 7 in. dia. stack	0.606(equivalent to one hole of 7/8 in. diameter)
2. Hy-Lo 148 Special	0.606(equivalent to one hole of 7/8 in. diameter)
3. Hy-Lo 230	0.606(equivalent to one hole of 7/8 in. diameter)
4. Lazy Flame 24 in. stack	0.606(equivalent to one hole of 7/8 in. diameter)
5. Lazy Flame 18 in. stack	1.212(equivalent to two holes of 7/8 in. diameter)
6. National Junior	1.212(equivalent to two holes of 7/8 in. diameter)

may not be used or operated for the purpose of giving protection from frost damage unless the primary air orifice(s) is (are) so adjusted or regulated to a maximum opening of not greater than the area designated above.

g. (Amended 1-16-58) Any new complete orchard or citrus grove heating equipment of the distilling type not listed in subsection "e" and "f" of this rule must contain a primary air orifice of such design that not more than one (1) gram per minute of unconsumed solid carbonaceous matter is emitted.

h. (Amended 1-16-58) No heater may be placed, be permitted to be placed or be permitted to remain in any orchard or citrus grove or in any other place where heaters may be fired to furnish protection from frost damage unless a permit or conditional permit has been issued.

i. (Amended 1-16-58) The use or operation of any partial assembly of any type heater for the purpose of giving protection from frost damage is hereby prohibited. A permit or conditional permit issued for the use or operation of any type orchard or citrus grove heater is for the use or operation of a complete heater assembly.

REGULATION VII. EMERGENCIES

(Revised 7-26-56) This emergency regulation is designed to prevent the excessive buildup of air contaminants and to avoid any possibility of a catastrophe caused by toxic concentrations of air contaminants. Past history indicates that the possibility of such a catastrophe is extremely remote.

The Air Pollution Control Board deems it desirable to have ready an adequate plan to prevent such an occurrence, and in case of the happening of this unforeseen event, to provide for adequate actions to protect the health of the citizens in the Air Pollution Control District.

RULE 150. (Adopted 6-20-55) GENERAL

Notwithstanding any other provisions of these rules and regulations, the provisions of this regulation shall apply within the Los Angeles Basin to the control of emissions of air contaminants during any "alert" stage as provided herein.

RULE 151. (Amended 1-16-58) SAMPLING STATIONS

The Air Pollution Control Officer shall maintain at least six (6) permanently located atmospheric sampling stations adequately equipped. These sampling stations shall be continuously maintained at locations designated by the Air Pollution Control Officer after consultation with the Scientific Committee. The Air Pollution Control Officer may maintain such additional sampling stations as may be necessary. These additional stations may be permanent, temporary, fixed, or mobile, and may be activated upon orders of the Air Pollution Control Officer.

RULE 152. (Revised 7-26-56) AIR SAMPLING

The Air Pollution Control Officer shall establish procedures whereby adequate samplings and analyses of air contaminants will be taken at each of the stations established under RULE 151.

RULE 153. (Adopted 6-20-55) REPORTS

The Air Pollution Control Officer shall make daily summaries of the readings required by Rule 152. The summaries shall be in such form as to be understandable by the public. These summaries shall be public records and immediately after preparation shall be filed at the main office of the Air Pollution Control District and be available to the public, press, radio, television, and other mass media of communication.

RULE 154. (Revised 7-26-56) CONTINUING PROGRAM OF VOLUNTARY COOPERATION

Upon the adoption of this regulation the Air Pollution Control Officer shall inform the public of ways in which air pollution can be reduced and shall request voluntary cooperation from all persons in all activities which contribute to air pollution. Civic groups shall be encouraged to undertake campaigns of education and voluntary air pollution reduction in their respective communities. Public officials shall be urged to take promptly such steps as may be helpful to reduce air contamination to a minimum within the areas of their authority. Employers shall be requested to establish car pools. Users of automotive vehicles shall be urged to keep motors in good condition and to plan routes and schedules which will contribute minimum contamination to critical areas of pollution. All industrial, commercial and business establishments which emit hydrocarbons or the air contaminants named in RULE 156 should critically study their operations from the standpoint of air contamination and should take appropriate action voluntarily to reduce air pollution.

RULE 154.1. PLANS

a. (Revised 7-26-56) If the Air Pollution Control Officer finds that any industrial, business or commercial establishment or activity emits

hydrocarbons or any of the contaminants named in Rule 156, he may give written notice to the owner or operator of such industrial, business or commercial establishment or activity to submit to the Air Pollution Control Officer plans for immediate shutdown or curtailment, in the event of an air pollution emergency, all of the sources of hydrocarbons or any of the contaminants named in RULE 156, including vehicles owned or operated by such person, his agents or employees in the scope of the business or operation of such establishment or activity. Such plans shall include, in addition to the other matters set forth in this rule, a list of all such sources of hydrocarbons and and any of the contaminants named in RULE 156, and a statement of the minimum time and the recommended time to effect a complete shutdown of each source in the event of an air pollution emergency. Such notice may be served in the manner prescribed by law for the service of summons, or by registered or certified mail. Each such person shall, within sixty (60) days after the receipt of such notice, or within such additional time as the Air Pollution Control Officer may specify in writing, submit to the Air Pollution Control Officer the plans and information described in the notice.

b. (Revised 7-26-56) The Air Pollution Control Officer shall prepare appropriate plans to be made effective and action to be taken in respect to a First or Second Alert as follows:

(Revised 7-26-56) In respect to a First Alert, the Air Pollution Control Officer shall develop plans calling for the operation of all privately owned vehicles on a pool basis as may be arranged by persons and employers of persons operating vehicles from home to work and in the business of such employer.

(Revised 7-26-56) In respect to a Second Alert, the Control Officer shall prepare a program of action and steps to be taken under the provisions of RULE 158, paragraph c. The general nature of the plans to be made effective upon a Second Alert shall be reported to and subject to review and approval by the Air Pollution Control Board.

(Revised 7-26-56) It shall be the objective of such program to result in bringing about a diminution of air contaminants which occasioned the Second Alert and to prevent any increase thereof in order to protect the health of all persons within the area affected by the alert. It shall also be the objective of such plans that they may be effective to curtail the operations of industrial, business, commercial and other activities within the basin, but without undue interference with the operations of public utilities or other productive, industrial, business and other activities, the conduct of which is is essential to the health and welfare of the community. It is further intended that any said plan of action shall not jeopardize the welfare of the public or result in irreparable injury to any means of production or distribution or the rendering of public utility services.

(Adopted 6-20-55) The Air Pollution Control Officer shall further, by cooperative agreements or in addition to cooperative agreements, prepare plans for action in respect to industry, business, transportation, hospitals, schools and other appropriate public and private institutions, and the public generally, to accomplish the purposes of the Second Alert action as set forth in Rule 158d. The general nature of the plans to be made effective upon a Second Alert shall be reported to and subject to review and approval by the Air Pollution Control Board.

(Adopted 6-20-55) All plans and programs of action to make effective the procedures prescribed in Rule 158, paragraphs c., and d., shall be consistent with and designed to accomplish the purposes, and shall be subject to the conditions and limitations, set forth in said paragraphs c., and d.

(Adopted 6-20-55) The Air Pollution Control Officer shall give, or cause to be given, wide publicity in regard to plans for action to be applicable under Rule 158, paragraphs c., and d., in order that all persons within the district shall be able to understand and be prepared to render compliance therewith in the event of the sounding of a Second Alert.

RULE 155. (Revised 7-26-56) DECLARATION OF ALERTS

The Air Pollution Control Officer shall declare the appropriate "alert" whenever the concentration of any air pollution contaminant has been verified to have reached the standards set forth in Rule 156.

RULE 155.1. (Adopted 7-26-56) NOTIFICATION OF ALERTS

Following the declaration of the appropriate "alert", the Air Pollution Control Officer shall communicate notification of the declaration of the alert to:

a. The Los Angeles County Sheriff and the Sheriff shall broadcast the declaration of the "alert" by the Sheriff's teletype and radio system to:

1. All Sheriff's substations.
2. All city police departments.
3. California Highway Patrol.

b. Local public officials and public safety personnel, who have responsibilities or interests in air pollution alerts.

c. Air polluting industrial plants and processes which require "alert" data in order to effect pre-arranged plans designed to reduce the output of air contaminants.

d. The general public.

e. All Air Pollution Control District personnel.

RULE 155.2. (Amended 3-2-67) RADIO COMMUNICATION SYSTEM

The Air Pollution Control Officer shall install and maintain, in continuous operation, a radio transmitter with selective calling facilities for the purpose of broadcasting the declaration of alerts and information and instructions which may be appropriate to carry out the provisions of this regulation.

Radio receiving equipment with decoding device capable of receiving broadcasts from the Air Pollution Control Officer of the declaration of alerts and information and instructions thereto shall be installed and properly maintained and operated during all hours of plant operation by any person who operates or uses any:

a. Petroleum refinery.

b. Bulk gasoline loading facility for tank vehicles, tank cars, or marine vessels, from which facility 20,000 gallons or more of gasoline are loaded per day. For purposes of this paragraph, "gasoline" means any petroleum distillate having a Reid vapor pressure of four pounds or greater, and "facility" means all gasoline loading equipment which is both: (1) possessed by one person, and (2) located so that all the gasoline loading outlets for such aggregation or combination of loading equipment can be encompassed within any circle of 300 feet in diameter.

c. Asphalt saturator.

d. Asphalt paving manufacturing plant.

e. Asphalt manufacturing plant.

f. Chemical plant which:

(1) Reacts or produces any organic liquids or gases.

(2) Produces sulfuric acid, nitric acid, phosphoric acid, or sulfur.

g. Paint, enamel, lacquer, or varnish manufacturing plant in which 10,000 gallons or more per month of organic solvents, diluents or thinners, or any combination thereof are combined or manufactured into paint, enamel, lacquer, or varnish.

h. Rubber tire manufacturing or rubber reclaiming plant.

i. Automobile assembly or automobile body plant.

j. Metal melting, refining or smelting plant in which a total of 2,500 pounds or more of metal are in a molten state at any one time or are poured in any one hour.

k. Rock wool manufacturing plant.

l. Glass or frit manufacturing plant in which a total of 4,000 pounds or more of glass or frit or both are in a molten state at any one time or are poured in any one hour.

RULE 156. (Adopted 6-20-55) ALERT STAGES FOR TOXIC AIR POLLUTANTS. (In parts per million of air)

	FIRST ALERT	SECOND ALERT	THIRD ALERT
CARBON MONOXIDE*	100	200	300
NITROGEN OXIDES*	3	5	10
SULFUR OXIDES*	3	5	10
OZONE*	0.5	1.0	1.5

FIRST ALERT: Close approach to maximum allowable concentration for the population at large. Still safe but approaching a point where preventive action is required.

SECOND ALERT: Air contamination level at which a health menace exists in a preliminary stage.

THIRD ALERT: Air contamination level at which a dangerous health menace exists.

*How measured: The concentrations of air contaminants shall be measured in accordance with the procedures and recommendations established by the Scientific Committee.

RULE 157. (Amended 12-4-58) FIRST ALERT ACTION

This is a warning alert and shall be called declared whenever the concentration of any contaminant has been verified to have reached the standards for the "first alert" set forth in Rule 156. The following

action shall be taken upon the calling of the First Alert:

a. A person shall not burn any combustible refuse at any location within the basin in an open fire.

b. Any person operating or maintaining any industrial, commercial or business establishment other than power plants or heating plants essential to health or safety, which establishments emit hydrocarbons or any of the contaminants named in Rule 156, and any person operating any private noncommercial vehicle, shall, during the First Alert period, take the necessary preliminary steps to the action required should a Second Alert be declared.

c. The Air Pollution Control Officer shall, by the use of all appropriate mass media of communication, request the public to stop all unessential use of vehicles in the basin and to operate all privately owned vehicles on a pool basis, and shall request all employers to activate employee car pools.

d. When, after the declaration of the First Alert it appears to the Air Pollution Control Officer that the concentration of any contaminants in all or any portion of the basin is increasing in such a manner that a Second Alert is likely to be called, he shall take the following actions:

(1) Notify the Emergency Action Committee and request advice on actions to be taken.

(2) Give all possible notice to the public by all mass media of communication that a Second Alert may be called.

RULE 158. (Revised 7-26-56) SECOND ALERT ACTION

This is a preliminary health hazard alert and shall be declared when an air contaminant has been verified to have reached the standards set forth for the "Second Alert" in Rule 156.

The following action shall be taken upon the calling of the Second Alert:

a. (Adopted 6-20-55) The action set forth in Rule 157, and

b. (Adopted 6-20-55) The Emergency Action Committee and the Air Pollution Control Board, if not already activated, shall be called into session and shall remain in session or reconvene from time to time as directed by the Air Pollution Control Officer to study all pertinent information relating to the emergency and to recommend to the Air Pollution Control Officer actions to be taken from time to time as conditions change.

c. (Revised 7-26-56) The Air Pollution Control Officer shall make effective, upon notice as provided in Rule 155.1, the program of action to be taken as previously developed pursuant to Rule 154.1, paragraph b., and to carry out the policy stated therein.

(Revised 7-26-56) Pursuant to this alert, the Air Pollution Control Officer may impose limitations as to the general operation of vehicles as provided in Rule 154.1, permitting limited operation essential to accommodate industry, business, public utility and other services as may be necessary in the public welfare.

d. (Adopted 6-20-55) In the event the control measures made effective under paragraph c. above prove to be inadequate to control the increase in the concentration of air contaminants, the Air Pollution Control Officer, with the advice of the Emergency Action Committee and with the concurrence of the Air Pollution Control Board shall take such steps as he may deem necessary to assure adequate control of existing air contaminants and to protect the health and safety of the public, but, if possible, without employing such drastic remedial measures as to completely disrupt the economic life of the community or to result in irreparable injury to any form of production, manufacture or business.

(Revised 7-26-56) The Air Pollution Control Officer may, with the concurrence of the Air Pollution Control Board, order the closing of any industrial, commercial or business establishment and stop all vehicular traffic, except authorized emergency vehicles as defined in the California Vehicle Code, vehicles used in public transportation and vehicles the operation of which is necessary for the protection of the health and welfare of the public, if in the opinion of the Air Pollution Control Officer, the continued operation of such establishment or vehicle contributes to the further concentration of any air contaminant, the concentration of which caused the declaration of the "alert".

(Revised 7-26-56) The Air Pollution Control Officer, during a Second Alert, shall keep the public suitably informed of all significant changes in the concentration of toxic air contaminants.

e. (Adopted 9-28-61) In the event that the Air Pollution Control Officer determines that the public health and safety is in danger, the

Emergency Action Committee and the Air Pollution Control Board may take any action authorized by this rule with less than a quorum present. A majority vote of the members present is required for any such action.

RULE 159. (Revised 7-26-56) THIRD ALERT

This is a dangerous health hazard alert and shall be declared when an air contaminant has been verified to have reached the standards set forth for the "Third Alert" in Rule 156.

The following action shall be taken upon the calling of the Third Alert:

a. (Adopted 6-20-55) The actions set forth in Rules 157 and 158, and

b. (Adopted 6-20-55) If it appears that the steps taken by the Air Pollution Control Officer will be inadequate to cope with the emergency, the Air Pollution Control Board shall request the Governor to declare that a state of emergency exists and to take appropriate actions as set forth in the California Disaster Act.

RULE 160. (Revised 7-26-56) END OF ALERT

The Air Pollution Control Officer shall declare the termination of the appropriate alert whenever the concentration of an air contaminant which caused the declaration of such alert has been verified to have fallen below the standards set forth in Rule 156 for the calling of such alert and the available scientific and meteorological data indicates that the concentration of such air contaminant will not immediately increase again so as to reach the standards set forth for such alert in Rule 156. The Air Pollution Control Officer shall immediately communicate the declaration of the termination of the alert in the manner provided in Rule 155.1 for the declaration of alerts. The Sheriff shall broadcast the termination of the alert in the same manner as provided in Rule 155.1 for the declaration of alerts.

RULE 161. (Revised 7-26-56) ENFORCEMENT

When an "alert" has been called the Air Pollution Control Officer, the Sheriff, their deputies, and all other peace officers within the Basin shall enforce the appropriate provisions of this regulation and all orders of the Air Pollution Control Board or the Air Pollution Control Officer made pursuant to this regulation against any person who, having knowledge of the declaration of an alert, refuses to comply with the rules set forth in this regulation or any order of the Air Pollution Control Board or the Air Pollution Control Officer made pursuant to this regulation.

RULE 163. (Revised 7-26-56) SCIENTIFIC COMMITTEE

A Scientific Committee shall be appointed by the Air Pollution Control Board. Members shall be licensed physicians, medical scientists, biologists, chemists, engineers, or meteorologists, each of whom has had experience in air pollution control work, or other experts with scientific training.

(Adopted 6-20-55) The Air Pollution Control Officer and the County Counsel shall be ex-officio members of the Scientific Committee.

(Adopted 6-20-55) The term of appointment of all members except the ex-officio members shall be two (2) years. The Scientific Committee shall act through a majority. There shall be at least fifteen (15) members on the Committee.

The Scientific Committee shall have the following duties:

a. (Revised 7-26-56) Study and recommend. The Scientific Committee shall study and make recommendations to the Air Pollution Control Board of the most suitable methods for measurement of air contaminants and on any changes recommended for the concentrations set forth in RULE 156. The Air Pollution Control Board may adopt such recommended changes for the concentrations of toxic air contaminants for each alert staged by amendment to RULE 156.

b. (Adopted 6-20-55) Consult. The Scientific Committee shall serve in a consultant advisory capacity to the Air Pollution Control Officer concerning any air pollution health problem which may arise. The Scientific Committee shall also advise the Air Pollution Board on any recommended changes in this emergency regulation which will provide greater protection of the health and welfare of all persons within the Air Pollution Control District.

RULE 164. (Revised 9-28-61) EMERGENCY ACTION COMMITTEE

An Emergency Action Committee shall be appointed by the Air Pollution Control Board. The committee shall be composed of ten (10) appointed members and of these members two shall be experts with scientific training or knowledge in air pollution matters, two shall be licensed physicians, two shall be representatives of industry, two shall be representatives of law enforcement, and two shall be members of the public at large.

The County Health Officer, the Sheriff, and the County Counsel shall be ex-officio members of the

Committee. In the absence of an ex-officio member, his deputy may act for him.

The term of appointment of appointed members shall be two years.

The duties of the Emergency Action Committee shall be to meet with the Air Pollution Control Officer when called into session, to evaluate data, and to advise the Air Pollution Control Officer as to the appropriate action to be taken when the concentration of any of the contaminants set forth in Rule 156 has been verified to be approaching the standards set forth in Rule 156 for a Second Alert.

The Committee shall meet when called into session and not less than every three months.

APPENDIX B

APPENDIX B: ODOR-TESTING TECHNIQUES

Modern technology has not yet produced a precise method of analyzing odor concentration or odor quality. In some instances, it has been possible to measure concentrations of specific odorous compounds through chemical or spectroscopic analyses. The odors of concern to air pollution engineers, however, are usually mixtures of several odorous compounds (McCord and Witheridge, 1949). Identification and measurement of each constituent is usually a tedious, if not impossible, task. For this reason, it is more practical to measure the aggregate odor concentration or detectability of a gas stream in terms of odor units. An odor unit is defined as the quantity of any odor or mixture of odors that, when dispersed in one cubic foot of odor-free air, produces a median threshold odor detection response. The overall odor measurement techniques to determine odor units require that human olfactory organs serve as analytical tools. Inasmuch as olfactory responses are somewhat transitory, particular care must be taken to eliminate extraneous odors and false olfactory responses.

A dilution method has been developed (Fox and Gex, 1957) that uses the human nose to measure odor concentration. It generally follows the American Society for Testing Materials Method D1391-57 (Standard Method for Measurement of Odor in Atmospheres [Dilution Method]) and incorporates some refinements. The method consists, in essence, of successively diluting a gas sample with odor-free air until a threshold dilution is reached, that is, at further dilution no odor is detectable by the human nose. To minimize the effect of variations in olfactory systems, a panel of several persons is used. The odor concentration is determined by plotting dilution response data on log-probability coordinates.

This dilution method serves principally to measure odor concentration. It is a valuable tool with which to evaluate the performance of odor control equipment, and the quantitative odor nuisance potential of a source. The quality or objectionability of an odor cannot be evaluated with the same assurance. While the dilution method can be used to measure objectionability thresholds, results are not as reproducible as detectability measurements are. This is due principally to the subjective nature of human olfactory responses. The average subject can report the presence or absence of an odor with more certainty than he can determine objectionability.

Odor testing is a comparatively recent development. Certain modifications (Mills et al., 1963) of the American Society for Testing Materials static test procedure were developed to accommodate the method to field problems and to accelerate the testing procedure, at the same time maintaining or improving the reproducibility and reliability of results.

For employment of this method for odor evaluation, a selected group of individuals must be used as odor panel members, and an air-conditioned, odor-free room must be used for the test.

THE ODOR PANEL

The ASTM procedure describes a suitable method of screening and selecting members of the odor panel. The selectees should be persons who are neither the most sensitive to odors nor the most insensitive of those screened. The choice of panel members should be limited to those with the most generally reliable olfactory perception.

Consistent and reproducible results have been found to be obtained with a panel consisting of at least eight persons. Although a panel of six persons is adequate at times, eight is preferred, because the probabilities of inconclusive results (with the resultant necessity of rerunning the test) are thereby reduced.

If possible, the panel members should be allowed to relax in the odor-free room for 10 to 15 minutes before the test. This ensures that their olfactory senses are not fatigued or dulled by extraneous odors. Test periods should be limited to 30 minutes or less. If testing is required over a longer period, adequate rest periods should be scheduled to preclude fatigue.

THE ODOR EVALUATION ROOM

A typical plan for an odor evaluation room is shown in Figure B1. Essential features are: (1) Separation of the work area from the evaluation area, (2) provision for relatively odor-free air at room temperature with moderate humidity by use of an air-conditioning unit, and (3) an activated-carbon adsorption unit to provide and circulate odor-free air to the evaluation area.

An odor evaluation room should be designed to minimize the possibility of extraneous odors in the vicinity of the panelists. It should be devoid of fabrics, such as carpeting, draperies, or upholstery, that might hold odorous materials. The room should be so located in the building that

there is no introduction of odors into the air conditioner inlet or through doors, cracks, and so forth. Air circulation should be such that the activated-carbon unit discharges air near the panelists. All air from the work area should be filtered before it comes into contact with panelists.

SAMPLING TECHNIQUES

Representative sampling points are chosen according to standard air-sampling techniques. In most instances, 250-milliliter grab samples are sufficient. These are collected in gas-sampling tubes such as those shown in Figure B2. Possible sources of error are foreign odors from the sampling train, improperly cleaned glassware, and condensation in the sample tube.

The use of rubber or plastic tubing and other heat-sensitive materials in the sample probe should be avoided, particularly if the gas stream is at an elevated temperature. The apparatus of Figure B2 is recommended wherein all tubing and joints upstream of the sampling tube are constructed of glass. The rubber bulb evacuator is on the downstream side of the tube and does not contaminate the sample.

The problems of condensation and adsorption of odorous material on the inner walls of the sampling apparatus are the most difficult to overcome or even to evaluate. Odor adsorption can be minimized by flushing the sampling equipment with enough of the gas stream to allow temperature and humidity to reach equilibrium. The area of ground glass in contact with the sample should be held to a minimum.

Condensation in the tube can introduce a large error when the moisture content is much more than 20 percent by volume. When the gas stream bears a high moisture content, a second sampling technique has been devised in which the sample is diluted in the sample tube with dry, odor-free air. Dilution air is drawn through a cartridge charged with activated carbon and a suitable dessicant. This sampling technique provides a dilution of 10:1 or greater in the tube. Equipment used for dilution sampling is diagrammed in Figure B3. The 1-millimeter-outside-diameter capillary tube used as a probe is inserted through a new, size 000, cork stopper with the aid of an 18-gage hypodermic needle as a sleeve. The sample is obtained by placing the free end of the capillary into the gas stream and withdrawing the required 5 to 10 milliliters of air from the sample tube with the 10-milliliter syringe. The volume withdrawn is replaced by an equal volume, which enters through the capillary tube. The small diameter of the capillary minimizes diffusion across the tube.

In both techniques, the stopcock nearest the squeeze bulb is closed first. When equilibrium conditions are established, the other stopcock is closed and the probe removed from the gas stream.

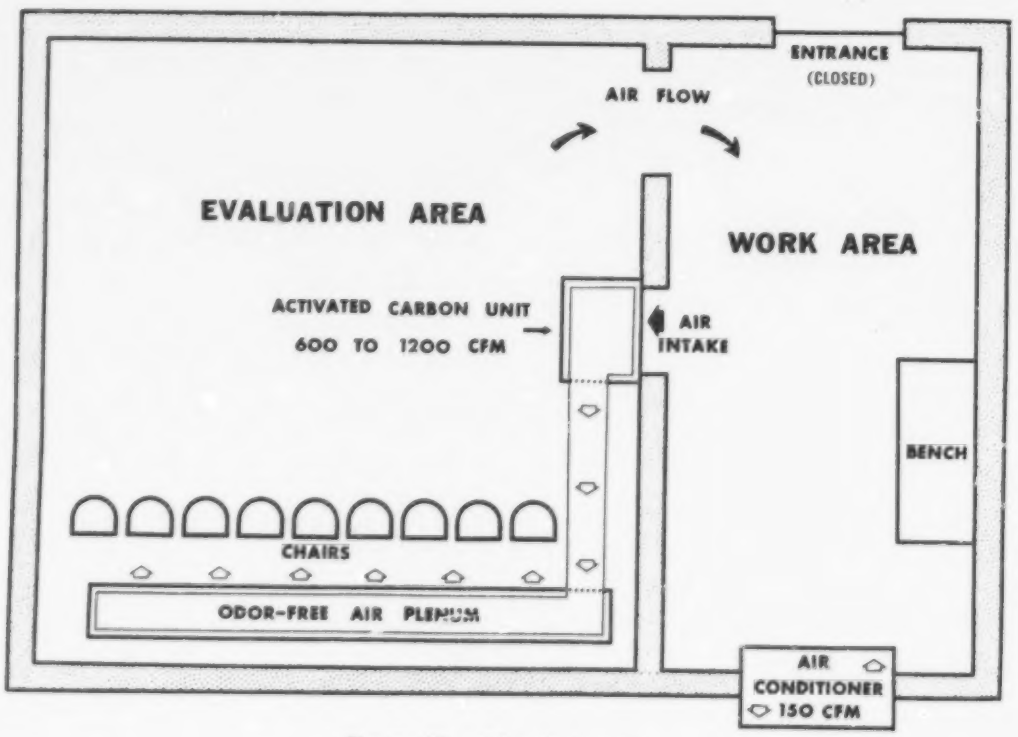


Figure B1. Odor-free room.

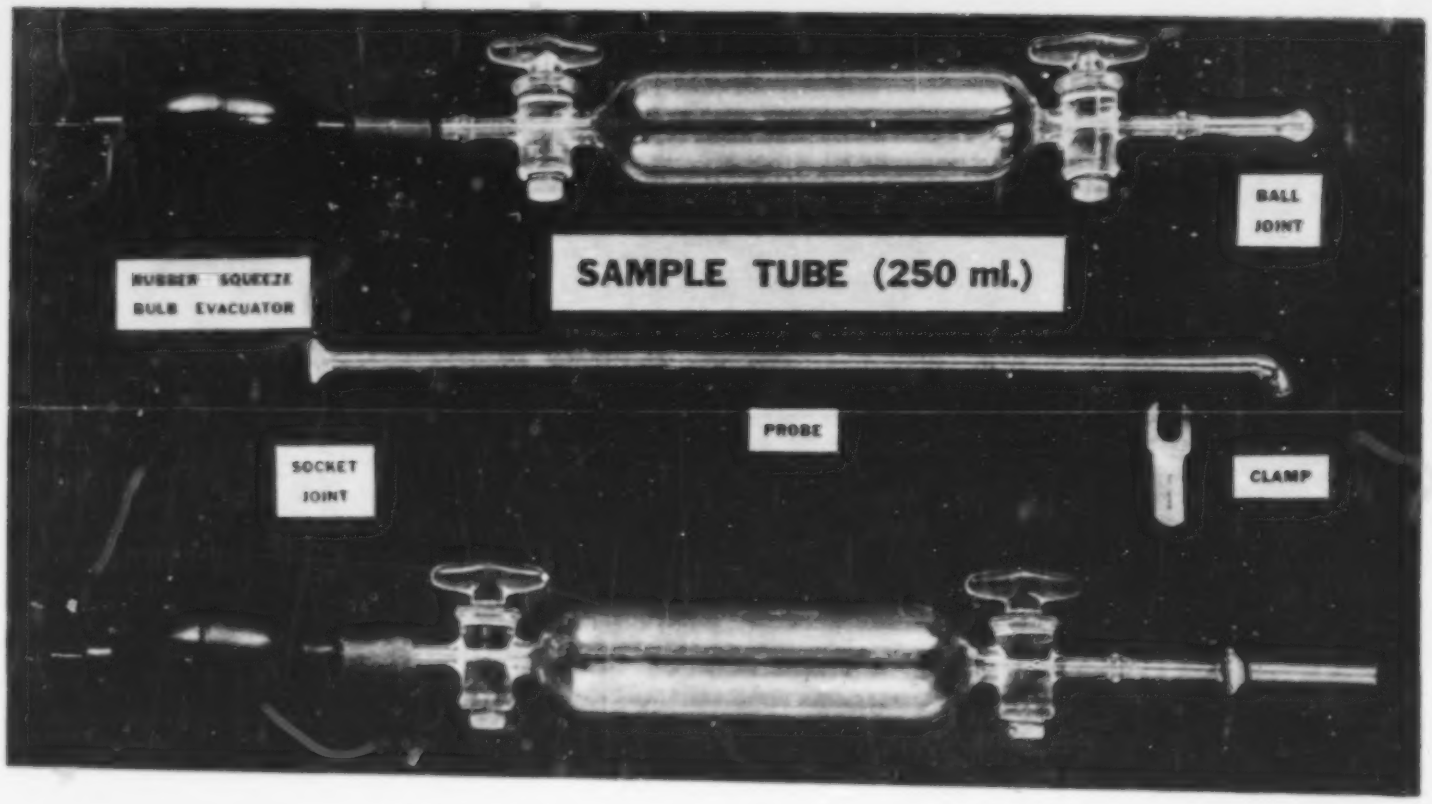


Figure B2. Odor sampling equipment for dry gases.

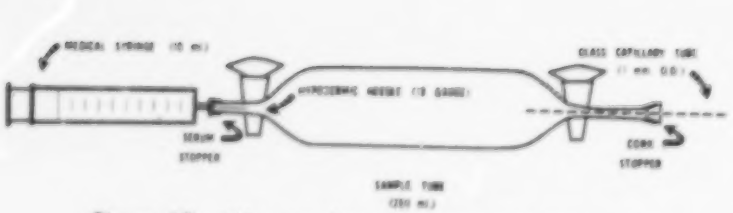


Figure B3. Odor sampling equipment for wet gases.

EVALUATION OF ODOR SAMPLES

In the work area of the odor evaluation room, mercury displacement is used to transfer the odorous gases from the sample tube to a 100-milliliter glass syringe. Figure B4 shows schematically the equipment needed. Ten milliliters is drawn into a syringe, and then 90 milliliters of odor-free air. This provides a 10:1 dilution. Further dilutions are made in other syringes including the panel member's syringe.

The last dilution (usually 10:1) is performed by the panelist, who is furnished with 10 milliliters of sample injected into his 100-milliliter syringe. He dilutes the sample to 100 milliliters with ambient air before sniffing. Most panelists prefer to eject the sample near their noses. Each panel member should, however, choose the method of smelling the sample by which he feels his results are most accurate and reproducible. He records

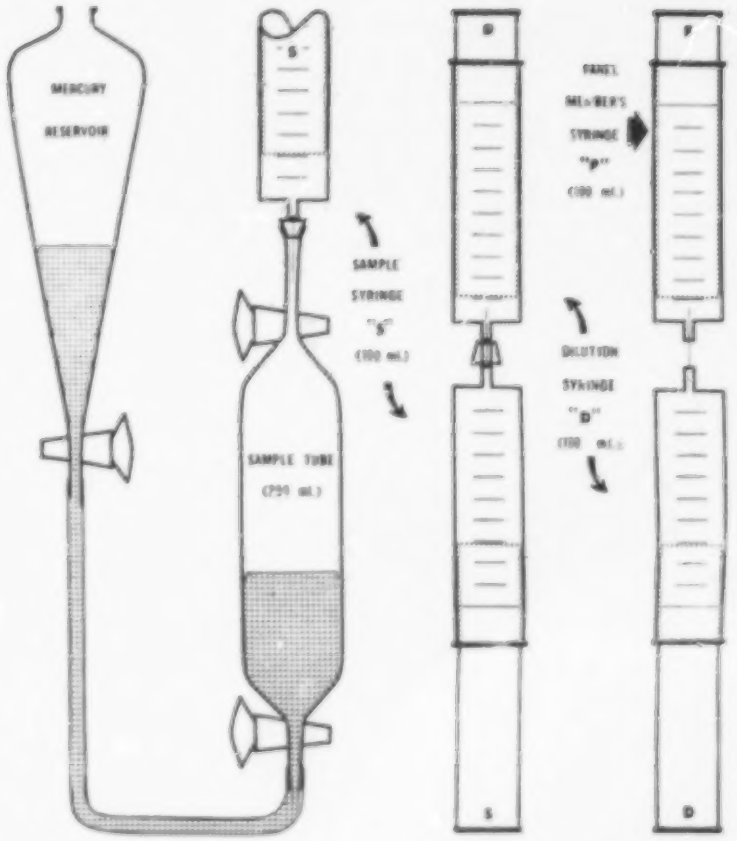


Figure B4. Equipment used for transferring and diluting odor samples.

a positive or negative detection of odors on a tally sheet together with the number of the sample. Each panelist purges his syringe with air between samples.

Some compounds such as aldehydes deaden the sense of smell and cause erratic results, that is, the dilution response data do not plot to a straight line on log-probability coordinates. While there is no entirely satisfactory method of overcoming this effect, it can be at least partially offset by allowing more time between samples for panelists' olfactory systems to recover.

DETERMINATION OF ODOR CONCENTRATION

The odor responses of the panel are quantified by calculating the percent of the panel members detecting odors at each dilution, as shown in Table B1. The ratio of the diluted volume to the original sample is termed the dilution factor. Odor responses are plotted against dilution factors to determine odor concentration.

Dilution response data follow a cumulative normal distribution curve. If plotted on rectilinear coordinates, these data produce an s-shaped curve. The points at the extremes of the curve would represent panelists who are the most and the least sensitive to the particular odors. The area in the middle of the curve would represent average olfactory responses.

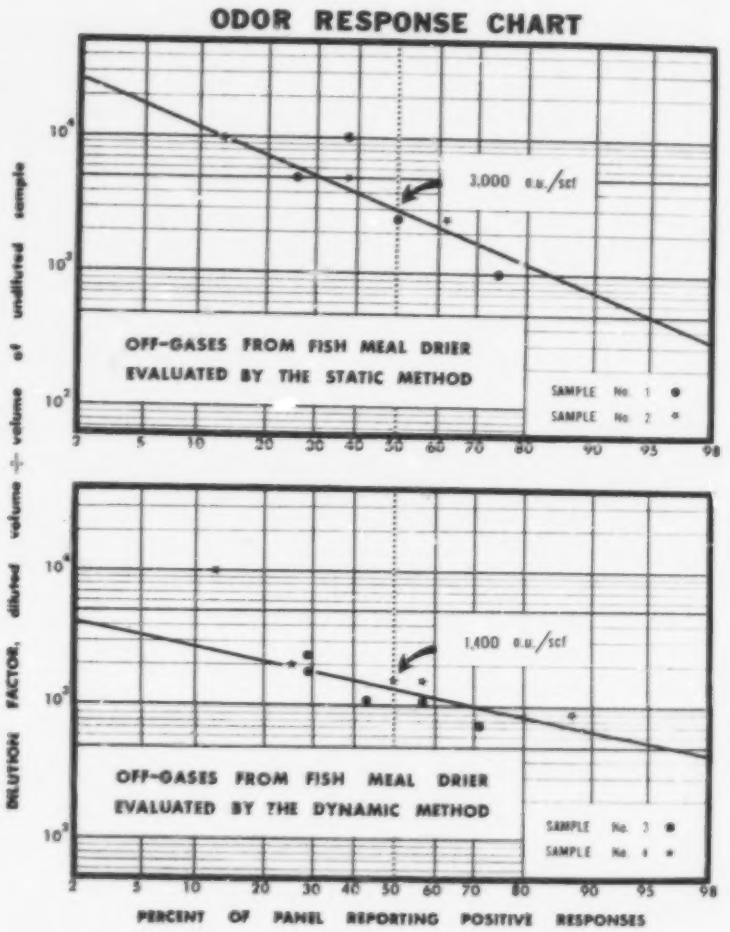

ODOR RESPONSE CHART
DILUTION FACTOR, diluted volume ÷ volume of undiluted sample
3,000 o.u./scf
OFF-GASES FROM FISH MEAL DRIER
EVALUATED BY THE STATIC METHOD
SAMPLE No. 1
SAMPLE No. 2
1,400 o.u./scf
OFF-GASES FROM FISH MEAL DRIER
EVALUATED BY THE DYNAMIC METHOD
SAMPLE No. 3
SAMPLE No. 4
PERCENT OF PANEL REPORTING POSITIVE RESPONSES

Figure B5. Plot of dilution response data.

When dilution response data are plotted on logarithmic-probability coordinates, they tend to follow a straight line. This phenomenon is shown in Figure B5, where the test data of Table B1 are plotted. The subject gases evaluated were replicate samples of discharge gases from a fish meal drier. The data plot to a reasonably straight line. Maximum deviation from a straight line is principally a function of the number of panelists.

The point at which the plotted line crosses the 50 percent panel response line is the threshold concentration. The dilution factor at the threshold is the odor concentration, usually stated in terms of odor units per scf. The total rate of odor emission in odor units per minute may then be calculated by multiplying the concentration by the total volume of the effluent.

Table B1. DATA FROM A TYPICAL DILUTION TEST

Sample No.	Dilution designation	Dilution factor[a]	No. of panel members	No. of panel members detecting odor	% of panel members detecting odor[b]
1	A	1,000	8	6	75
	B	2,500	8	4	50
	C	10,000	8	3	38
	D	5,000	8	2	25
2	A	2,500	8	5	63
	B	5,000	8	3	38
2	C	10,000	8	1	13

[a] The dilution factor is the volume of the diluted sample evaluated by the panel members, divided by the volume of the original undiluted sample contained therein.

[b] Zero and 100 percent responses are considered indeterminate.

APPENDIX C

APPENDIX C: HYPOTHETICAL AVAILABLE HEATS FROM NATURAL GAS

Burners for combustion devices such as afterburners frequently use the oxygen present in the contaminated effluent stream. An example would be a natural gas-fired afterburner that takes in 60 percent of its combustion air from the atmosphere, and 40 percent from an air containing contaminated effluent stream.

One step in checking afterburner design is the calculation of the natural gas flow rate required to raise an effluent stream to a given temperature. A calculation such as this normally makes use of the available heat from natural gas. Available heat is the amount of heat remaining after the products of combustion from a cubic foot of natural gas are raised to the afterburner temperature. Available heat from natural gas is shown in Table D7.

If the afterburner gas burner takes a portion of the combustion air from the effluent stream, then the calculation of the gas flow rate becomes a trial-and-error procedure. By the method of hypothetical available heats given here, the trial-and-error solution is eliminated.

The natural gas used in illustrating this calculation procedure requires 10.36 cubic feet of air for theoretical combustion of 1 cubic foot of gas (Los Angeles area natural gas). Products of complete combustion evolved from this process are carbon dioxide, water, and nitrogen. If the combustion of 1 cubic foot of natural gas is thought of as taking place at 60°F, then a portion of the heat released by combustion must be used to raise the products of combustion from 60°F to the temperature of the device. The remaining heat is called available heat. This quantity represents the heat from natural gas that can be used to do useful work in the combustion device, such as heating an effluent stream in an afterburner.

Consider a gas-fired afterburner adjusted to provide a fraction, X, of theoretical air through the burner. If the contaminated effluent contains air, then the remaining air for combustion, 1-X, is taken from the effluent stream. This means that a smaller quantity of effluent has to be heated by the natural gas, since a portion of the effluent is involved in the combustion reaction. Thus, a burner taking combustion air from an effluent stream can be fired to raise the temperature of the effluent at a natural gas input lower than that of a burner firing with all combustion air taken from the atmosphere.

Let the heat content of an effluent stream, at the desired final temperature, be H Btu/lb. Since 10.36 cubic feet of air is required for combustion of 1 cubic foot of natural gas, the weight of air taken from the effluent would be

$$W = (10.36)(1-X)(\rho) \qquad (C1)$$

The heat contents of this secondary combustion air would be

$$Q = WH = (10.36)(1-X)(\rho)(H) \qquad (C2)$$

where

W = weight of combustion air from the effluent per cubic foot of natural gas, lb/ft^3 natural gas

H = heat content of the effluent at the required temperature, Btu/lb

X = fraction of theoretical combustion air, furnished as primary air through burner

ρ = density of air at 60°F

= 0.0764 lb/ft^3.

Since Q Btu per cubic foot of natural gas is not required to heat the effluent, it can be added to the available heat, A, at the afterburner temperature, or

$$A' = A + Q \qquad (C3)$$

where

A' = hypothetical available heat, Btu/ft^3 natural gas

Q = heat content of secondary combustion air from equation C2.

Equation C3 is given in terms of temperature in the following equations:

Temperature, °F	Hypothetical available heat, Btu/ft^3 natural gas
600	871 + 104 (1-X)
700	846 + 124 (1-X)
800	821 + 144 (1-X)
900	798 + 167 (1-X)
1,000	773 + 185 (1-X)
1,100	747 + 206 (1-X)

APPENDIX C: HYPOTHETICAL AVAILABLE HEATS FROM NATURAL GAS

Burners for combustion devices such as afterburners frequently use the oxygen present in the contaminated effluent stream. An example would be a natural gas-fired afterburner that takes in 60 percent of its combustion air from the atmosphere, and 40 percent from an air containing contaminated effluent stream.

One step in checking afterburner design is the calculation of the natural gas flow rate required to raise an effluent stream to a given temperature. A calculation such as this normally makes use of the available heat from natural gas. Available heat is the amount of heat remaining after the products of combustion from a cubic foot of natural gas are raised to the afterburner temperature. Available heat from natural gas is shown in Table D7.

If the afterburner gas burner takes a portion of the combustion air from the effluent stream, then the calculation of the gas flow rate becomes a trial-and-error procedure. By the method of hypothetical available heats given here, the trial-and-error solution is eliminated.

The natural gas used in illustrating this calculation procedure requires 10.36 cubic feet of air for theoretical combustion of 1 cubic foot of gas (Los Angeles area natural gas). Products of complete combustion evolved from this process are carbon dioxide, water, and nitrogen. If the combustion of 1 cubic foot of natural gas is thought of as taking place at 60°F, then a portion of the heat released by combustion must be used to raise the products of combustion from 60°F to the temperature of the device. The remaining heat is called available heat. This quantity represents the heat from natural gas that can be used to do useful work in the combustion device, such as heating an effluent stream in an afterburner.

Consider a gas-fired afterburner adjusted to provide a fraction, X, of theoretical air through the burner. If the contaminated effluent contains air, then the remaining air for combustion, 1-X, is taken from the effluent stream. This means that a smaller quantity of effluent has to be heated by the natural gas, since a portion of the effluent is involved in the combustion reaction. Thus, a burner taking combustion air from an effluent stream can be fired to raise the temperature of the effluent at a natural gas input lower than that of a burner firing with all combustion air taken from the atmosphere.

Let the heat content of an effluent stream, at the desired final temperature, be H Btu/lb. Since 10.36 cubic feet of air is required for combustion of 1 cubic foot of natural gas, the weight of air taken from the effluent would be

$$W = (10.36)(1-X)(\rho) \qquad (C1)$$

The heat contents of this secondary combustion air would be

$$Q = WH = (10.36)(1-X)(\rho)(H) \qquad (C2)$$

where

W = weight of combustion air from the effluent per cubic foot of natural gas, lb/ft^3 natural gas

H = heat content of the effluent at the required temperature, Btu/lb

X = fraction of theoretical combustion air, furnished as primary air through burner

ρ = density of air at 60°F

= $0.0764\ lb/ft^3$.

Since Q Btu per cubic foot of natural gas is not required to heat the effluent, it can be added to the available heat, A, at the afterburner temperature, or

$$A' = A + Q \qquad (C3)$$

where

A' = hypothetical available heat, Btu/ft^3 natural gas

Q = heat content of secondary combustion air from equation C2.

Equation C3 is given in terms of temperature in the following equations:

Temperature, °F	Hypothetical available heat, Btu/ft^3 natural gas
600	871 + 104 (1-X)
700	846 + 124 (1-X)
800	821 + 144 (1-X)
900	798 + 167 (1-X)
1,000	773 + 185 (1-X)
1,100	747 + 206 (1-X)

APPENDIX D

APPENDIX D: MISCELLANEOUS DATA

Table D1. PROPERTIES OF AIR

Temp, °F	Specific heat at constant pressure (C_p), Btu/lb-°F	Absolute viscosity (μ), lb/hr-ft	Thermal conductivity (k), Btu/hr-ft-°F	Prandtl No. ($C\mu/k$), (dimensionless)	Density (ρ), lb/ft^3 [a]
0	0.240	0.040	0.0124	0.77	0.0863
20	0.240	0.041	0.0128	0.77	0.0827
40	0.240	0.042	0.0132	0.77	0.0794
60	0.240	0.043	0.0136	0.76	0.0763
80	0.240	0.045	0.0140	0.77	0.0734
100	0.240	0.047	0.0145	0.76	0.0708
120	0.240	0.047	0.0149	0.76	0.0684
140	0.240	0.048	0.0153	0.76	0.0662
160	0.240	0.050	0.0158	0.76	0.0639
180	0.240	0.051	0.0162	0.76	0.0619
200	0.240	0.052	0.0166	0.76	0.0601
250	0.241	0.055	0.0174	0.76	0.0559
300	0.241	0.058	0.0182	0.76	0.0521
350	0.241	0.060	0.0191	0.76	0.0489
400	0.241	0.063	0.0200	0.76	0.0460
450	0.242	0.065	0.0207	0.76	0.0435
500	0.242	0.067	0.0214	0.76	0.0412
600	0.242	0.072	0.0229	0.76	0.0373
700	0.243	0.076	0.0243	0.76	0.0341
800	0.244	0.080	0.0257	0.76	0.0314
900	0.245	0.035	0.0270	0.77	0.0295
1,000	0.246	0.089	0.0283	0.77	0.0275
1,200	0.248	0.097	0.0308	0.78	0.0238
1,400	0.251	0.105	0.0328	0.80	0.0212
1,600	0.254	0.112	0.0346	0.82	0.0192
1,800	0.257	0.120	0.0360	0.85	0.0175
2,000	0.260	0.127	0.0370	0.83	0.0161

[a] ρ taken at pressure of 29.92 inches of mercury.

Table D2. THRESHOLD LIMIT VALUES (Copyright, 1966, American Conference of Governmental Industrial Hygienists)*

Substance	Recommended Values ppm[a]	mg/m^3 [b]
Acetaldehyde	200	360
Acetic acid	10	25
Acetic anhydride	5	20
Acetone	1,000	2,400
Acetonitrile	40	70
Acetylene dichloride, see 1, 2 Dichloroethylene		
Acetylene tetrabromide	1	14
Acrolein	0.1	0.25
Acrylonitrile-skin	20	45
Aldrin-skin	--	0.25
Allyl alcohol-skin	2	5
Allyl chloride	1	3
[c]Allyl glycidyl ether (AGE)	10	45
Allyl propyl disulfide	2	12
2 Aminoethanol, see Ethanolamine		
Ammonia	50	35
Ammonium sulfamate (Ammate)	--	15
n-Amyl acetate	100	525
Aniline-skin	5	19
[d]Anisidine (o, p-isomers)-skin	--	0.5
Antimony and compounds (as Sb)	--	0.5
ANTU (alpha naphthyl thiourea)	--	0.3
Arsenic and compounds (as As)	--	0.5
Arsine	0.05	0.2
Barium (soluble compounds)	--	0.5
[c]Benzene (benzol)-skin	25	80
[f]Benzidine-skin	--	A[1]
p-Benzoquinone, see Quinone		
[d]Benzoyl peroxide	--	5
Benzyl chloride	1	5
Beryllium	--	0.002
[e]Biphenyl, see Diphenyl		
Boron oxide	--	15
[c]Boron trifluoride	1	3
Bromine	0.1	0.7
Butadiene (1, 3-butadiene)	1,000	2,200
Butanethiol, see Butyl mercaptan		
2-Butanone	200	590
2-Butoxy ethanol (Butyl Cellosolve)-skin	50	240
[e]Butyl acetate (n-butyl acetate)	--	--
Butyl alcohol	100	300
tert. Butyl alcohol	100	300
[c]Butylamine-skin	5	15
[c]tert. Butyl chromate (as CrO3)-skin	--	0.1
n-Butyl glycidyl ether (BGE)	50	270
Butyl mercaptan	10	35
p-tert. Butyltoluene	10	60
Cadmium oxide fume	--	0.1
Calcium arsenate	--	1
Calcium oxide	--	5
Camphor	--	2
[d]Carbaryl (Sevin) (R)	--	5
Carbon dioxide	5,000	9,000
Carbon disulfide-skin	20	60
[e]Carbon monoxide	--	--
Carbon tetrachloride-skin	10	65
Chlordane-skin	--	0.5
Chlorinated camphene, -skin	--	0.5
Chlorinated diphenyl oxide	--	0.5
[e]Chlorine	--	--
Chlorine dioxide	0.1	0.3
[c]Chlorine trifluoride	0.1	0.4
[c]Chloroacetaldehyde	1	3
Chlorobenzene (monochlorobenzene)	75	350
Chlorobromomethane	200	1,050
2-Chloro-1, 3 butadiene, see Chloroprene		
Chlorodiphenyl (42% chlorine)-skin	--	1
Chlorodiphenyl (54% chlorine)-skin	--	0.5
1, Chloro, 2, 3 epoxypropane, see Epichlorhydrin		
2, Chloroethanol, see Ethylene chlorohydrin		
Chloroethylene, see Vinyl chloride		
[c]Chloroform (trichloromethane)	50	240
1-Chloro-1-nitropropane	20	100
Chloropicrin	0.1	0.7
Chloroprene (2-chloro-1, 3-butadiene)-skin	25	90
Chromic acid and chromates (as CrO3)	--	0.1
[e]Cobalt	--	--
Copper fume	--	0.1
Dusts and mists	--	1.0
[d]Cotton dust (raw)	--	1
Crag (R) herbicide	--	15
Cresol (all isomers)-skin	5	22
Cyanide (as CN)-skin	--	5
[e]Cyclohexane	--	--
Cyclohexanol	50	200
Cyclohexanone	50	200
[e]Cyclohexene	--	--
[d]Cyclopentadiene	75	200
2, 4-D	--	10
DDT-skin	--	1

*See Table D2 Footnotes, pages 876 and 878.

Substance	ppm[a]	mg/m³ [b]
DDVP-skin	--	1
Decaborane-skin	0.05	0.3
Demeton (R)-skin	--	0.1
Diacetone alcohol (4-hydroxy-4-methyl-2-pentanone)	50	240
1,2 Diaminoethane, see Ethylenediamine Diborane		
[e]1,2-Dibromoethane (ethylene dibromide)-skin	--	--
[c]o-Dichlorobenzene	50	300
p-Dichlorobenzene	75	450
Dichlorodifluoromethane	1,000	4,950
[d]1,3-Dichloro-5-dimethyl hydantoin	--	0.2
1,1,-Dichloroethane	100	400
1,2-Dichloroethane	50	200
1,2-Dichloroethylene	200	790
[c]Dichloroethyl ether-skin	15	90
Dichloromethane, see Methylenechloride		
Dichloromonofluoromethane	1,000	4.200
[c]1,1-Dichloro-1-nitroethane	10	60
1,2-Dichloropropane, see Propylenedichloride		
Dichlorotetrafluoroethane	1,000	7,000
Dieldrin-skin	--	0.25
Diethylamine	25	75
Diethylether, see Ethyl ether		
Difluorodibromomethane	100	860
[c]Diglycidyl ether (DGE)	0.5	2.8
Dihydroxybenzene, see Hydroquinone		
Diisobutyl ketone	50	290
Dimethoxymethane, see Methylal		
Dimethyl acetamide-skin	10	35
[d]Dimethylamine	10	18
Dimethylaminobenzene, see Xylidene		
Dimethylaniline (N-dimethylaniline)-skin	5	25
Dimethylbenzene, see Xylene		
[d]Dimethyl 1,2-dibro-2,2-dichloroethyl phosphate, (Dibrom) (R)	--	3
[d]Dimethylformanide-skin	10	30
2,6 Dimethylheptanone, see Diisobutyl ketone		
1,1-Dimethylhydrazine-skin	0.5	1
Dimethylsulfate-skin	1	5
Dinitrobenzene (all isomers)-skin	--	1
Dinitro-o-cresol-skin	--	0.2
Dinitrotoluene-skin	--	1.5
Dioxane (Diethylene dioxide)-skin	100	360
Dipropylene glycol methyl ether-skin	100	600

Substance	ppm[a]	mg/m³ [b]
[d]Di-sec, octyl phthalate (Di-2-ethylhexylphthalate	--	5
Endrin-skin	--	0.1
Epichlorhydrin-skin	5	19
EPN-skin	--	0.5
1,2-Epoxypropane, see Propyleneoxide		
2,3-Epoxy-1-propanol see Glycidol		
Ethanethiol, see Ethyl-mercaptan		
Ethanolamine	3	6
2 Ethoxyethanol-skin	200	740
2 Ethoxyethylacetate (Cellosolve acetate)-skin	100	540
Ethyl acetate	400	1,400
Ethyl acrylate-skin	25	100
Ethyl alcohol (ethanol)	1,000	1,900
[e]Ethylamine	--	--
[c, e]Ethylbenzene	--	--
Ethyl bromide	200	890
Ethyl chloride	1,000	2,600
Ethyl ether	400	1,200
Ethyl formate	100	300
[c, e]Ethyl mercaptan	--	--
Ethyl silicate	100	850
Ethylene chlorohydrin-skin	5	16
Ethylenediamine	10	25
Ethylene dibromide, see 1,2-Dibromoethane		
Ethylene dichloride, see 1,2-Dichloroethane		
[c]Ethylene glycol dinitrate-skin	0.2	1.2
Ethylene glycol monomethyl ether acetate, see Methyl cellosolve acetate		
[e]Ethylene imine-skin	--	--
Ethylene oxide	50	90
Ethylidine chloride, see 1,1-Dichloroethane		
Ferbam	--	15
Ferrovanadium dust	--	1
Fluoride (as F)	--	2.5
Fluorine	0.1	0.2
Fluorotrichloromethane	1,000	5,600
[c]Formaldehyde	5	6
Freon 11, see Fluorotrichloromethane		
Freon 12, see Dichlorodifluoromethane		
Freon 13B1, see Trifluoromonobromethane		
Freon 21, see Dichloromonofluoromethane		
Freon 112, see 1,1,2,2-Tetrachloro-1,2 difluoroethane		

Substance	ppm[a]	mg/m³ [b]
Freon 113, see 1,1,2-Trichloro, 1,2,2-trifluoroethane		
Freon 114, see Dichlorotetrafluoroethane		
Furfural-skin	5	20
Furfuryl alcohol	50	200
[f]Gasoline	--	A[6]
Glycidol (2,3-Epoxy-1-propanol)	50	150
Glycol monoethyl ether, see 2-Ethoxyethanol		
[e]Guthion, see Azinphosmethyl		
Hafnium	--	0.5
Heptachlor-skin	--	0.5
Heptane (n-heptane)	500	2,000
[d]Hexachloroethane-skin	1	10
Hexane (n-hexane)	500	1,300
2-Hexanone	100	410
Hexone	100	410
sec-Hexyl acetate	50	295
Hydrazine-skin	1	1.3
Hydrogen bromide	3	10
[c]Hydrogen chloride	5	7
Hydrogen cyanide-skin	10	11
Hydrogen fluoride	3	2
Hydrogen peroxide, 90%	1	1.4
Hydrogen selenide	0.05	0.2
[d]Hydrogen sulfide	10	15
Hydroquinone	--	2
[c]Iodine	0.1	1
[e]Iron oxide fume	--	--
Isoamyl alcohol	100	360
Isophorone	25	140
Isopropyl alcohol	400	980
Isopropylamine	5	12
Isopropylether	500	2,100
Isopropyl glycidyl ether (IGE)	50	240
Ketene	0.5	0.9
Lead	--	0.2
Lead arsenate	--	0.15
Lindane-skin	--	0.5
Lithium hydride	--	0.025
[d]L.P.G. (Liquified petroleum gas)	1,000	1,800
Magnesium oxide fume	--	15
Malathion-skin	--	15
[c]Manganese	--	5
Mercury-skin	--	0.1
Mercury (organic compounds)-skin	--	0.01
Mesityl oxide	25	100
Methanethiol, see Methyl mercaptan		
Methoxychlor	--	15
2-Methoxyethanol, see Methyl cellosolve		
Methyl acetate	200	610
Methyl acetylene (propyne)	1,000	1,650
[d]Methyl acetylene-propadiene mixture (MAPP)	1,000	1,800
Methyl acrylate-skin	10	35
Methylal (dimethoxymethane)	1,000	3,100
Methyl alcohol (methanol)	200	260
Methyl amyl alcohol, see Methyl isobutyl carbinol		
[c]Methyl bromide-skin	20	80
Methyl butyl ketone, see 2-Hexanone		
Methyl cellosolve-skin	25	80
Methyl cellosolve acetate-skin	25	120
[c]Methyl chloride	100	210
Methyl chloroform	350	1,900
Methylcyclohexane	500	2,000
Methylcyclohexanol	100	470
o-Methylcyclohexanone-skin	100	460
Methyl ethyl ketone (MEK), see 2-Butanone		
Methyl formate	100	250
Methyl isobutyl carbinol-skin	25	100
Methyl isobutyl ketone, see Hexone		
[c,d]Methyl mercaptan	10	20
[d]Methyl methacrylate	100	410
Methyl propyl ketone, see 2-Pentanone		
[c,g]Methyl styrene	100	480
[c]Methylene bisphenyl isocyanate (MDI)	0.02	0.2
Methylene chloride (dichloromethane)	500	1,740
Molybdenum (soluble compounds)	--	5
(insoluble compounds)	--	15
Monomethyl aniline-skin	2	9
[d]Morpholine-skin	20	70
Naphtha (coal tar)	200	800
Naphtha (petroleum)	500	2,000
[d]Naphthalene	10	50
β-Naphthylamine	--	A[2]
Nickel carbonyl	0.001	0.007
[d]Nickel, metal and soluble compounds	--	1
Nicotine-skin	--	0.5
[d]Nitric acid	2	5
p-Nitroaniline-skin	1	6
Nitrobenzene-skin	1	5
[d]p-Nitrochloro-benzene-skin	--	1
Nitroethane	100	310
[c]Nitrogen dioxide	5	9
[d]Nitrogen trifluoride	10	29
[c]Nitroglycerin- + EGDN-skin	0.2	2
Nitromethane	100	250
1-Nitropropane	25	90
2-Nitropropane	25	90
N-Nitrosodimethyl-amine (Di-methyl-nitrosoamine)-skin	--	A[3]

Substance	ppm[a]	mg/m^3 [b]
Nitrotoluene-skin	5	30
Nitrotrichloromethane, see Chloropicrin		
Octane	500	2,350
Oil mist (mineral)	--	5
Osmium tetroxide	--	0.002
[d]Oxygen difluoride	0.05	0.1
Ozone	0.1	0.2
Parathion-skin	--	0.1
Pentaborane	0.005	0.01
Pentachloronaphthalene-skin	--	0.5
Pentachlorophenol-skin	--	0.5
Pentane	1,000	2,950
2-Pentanone	200	700
Perchloroethylene	100	670
Perchloromethyl mercaptan	0.1	0.8
Perchloryl fluoride	3	13.5
Phenol-skin	5	19
[d]p-Phenylene diamine-skin	--	0.1
Phenylethylene, see Styrene		
Phenyl glycidyl ether (PGE)	50	310
Phenylhydrazine-skin	5	22
Phosdrin (Mevinphos) (R)-skin	--	0.1
[d]Phosgene (carbonyl chloride)	0.1	0.4
Phosphine	0.3	0.4
Phosphoric acid	--	1
Phosphorus (yellow)	--	0.1
Phosphorus pentachloride	--	1
Phosphorus pentasulfide	--	1
Phosphorus trichloride	0.5	3
[d]Phthalic anhydride	2	12
Picric acid-skin	--	0.1
Platinum (Soluble salts)	--	0.002
Polytetrafluoroethylene decomposition products	--	A[4]
[d]Propane	1,000	1,800
Propyne, see Methyl-acetylene		
βPropiolactone	--	A[5]
n-Propyl acetate	200	840
n-Propyl nitrate	25	110
Propylene dichloride	75	350
[e]Propylene imine-skin	--	--
Propylene oxide	100	240
Pyrethrum	--	5
Pyridine	5	15
Quinone	0.1	0.4
Rotenone (commercial)	--	5
[d]Selenium compounds (as Se)	--	0.2
[d]Silver, metal and soluble compounds	--	0.01
Sodium fluoroacetate (1080) - skin	--	0.05
Sodium hydroxide	--	2
Stibine	0.1	0.5
Stoddard solvent	500	2,900
Strychnine	--	0.15
[c]Styrene monomer (phenyl-ethylene)	100	420
Sulfur dioxide	5	13
Sulfur hexafluoride	1,000	6,000
Sulfuric acid	--	1
Sulfur monochloride	1	6
Sulfur pentafluoride	0.025	0.25
Sulfuryl fluoride	5	20
Systox, see Demeton		
2,4,5 T	--	10
Tantalum	--	5
TEDP - skin	--	0.2
Teflon (R) decomposition products	--	A[4]
Tellurium	--	0.1
TEPP - skin	--	0.05
[d]1,1,1,2-Tetrachloro-2,2-difluoroethane	500	4,170
1,1,2,2-Tetrachloro-1,2-difluoroethane	500	4,170
1,1,2,2-Tetrachloroethane-skin	5	35
Tetrachloroethylene, see Perchloroethylene		
Tetrachloromethane, see Carbon tetrachloride		
Tetraethyl lead (as Pb)-skin	--	0.075
Tetrahydrofuran	200	590
Tetranitromethane	1	8
Tetryl (2,4,6-trinitrophenyl-methylnitramine)-skin	--	1.5
Thallium (soluble compounds)-skin	--	0.1
Thiram	--	5
Tin (inorganic compounds, except oxide)	--	2
Tin (organic compounds)	--	0.1
Titanium dioxide	--	15
Toluene (toluol)	200	750
[c]Toluene-2,4-diisocyanate	0.02	0.14
o-Toluidine-skin	5	22
Toxaphene, see Chlorinated camphene		
1,1,1-Trichloroethane, see Methyl chloroform		
Trichloroethylene	100	535
Trichloromethane, see Chloroform		
Trichloronaphthalene-skin	--	5
1,2,3-Trichloropropane	50	300
1,1,2-Trichloro 1,2,2-trifluoroethane	1,000	7,600
Triethylamine	25	100
Trifluoromonobromomethane	1,000	6,100
2,4,6-Trinitrophenol see Picric acid		
2,4,6-Trinitrophenylmethyl-nitramine, see Tetryl		

Substance	ppm[a]	mg/m^3 [b]
Trinitrotoluene-skin	--	1.5
Triorthocresyl phosphate	--	0.1
Tripheryl phosphate	--	3
Turpentine	100	560
Uranium (soluble compounds)	--	0.05
(insoluble compounds)	--	0.25
[c]Vanadium (V_2O_5 dust)	--	0.5
(V_2O_5 fume)	--	0.1
Vinyl benzene, see Styrene		
[c]Vinyl chloride	500	1,300
Vinylcyanide, see Acrylonitrile		
Vinyl toluene	100	480
Warfarin	--	0.1
[e]Xylene (xylol)	--	--
Xylidine-skin	5	25
[d]Yttrium	--	1
Zinc oxide fume	--	5
Zirconium compounds (as Zr)	--	5

Radioactivity: For permissible concentrations of radioisotopes in air, see U.S. Department of Commerce, National Bureau of Standards, Handbook 69, "Maximum Permissible Body Burdens and Maximum Permissible Concentrations of Radionuclides in Air and in Water for Occupational Exposure," June 5, 1959. Also, see U.S. Department of Commerce National Bureau of Standards, Handbook 59, "Permissible Dose from External Sources of Ionizing Radiation," September 24, 1954, and addendum of April 15, 1958.

Note: Footnotes to Recommended Values.

[a]Parts of vapor or gas per million parts of air plus vapor by volume at 25°C and 760 mm. Hg pressure.
[b]Approximate milligrams of particulate per cubic meter of air.
[c]Indicates a value that should not be exceeded.
[d]1966 addition.
[e]See tentative limits.
[f]See A values on page 878.

Respirable Dusts Evaluated by Count

Substance	mp/ft^3 [a]
Silica	
Crystalline	
Quartz, threshold limit calculated from the formula	$\frac{250}{\%SiO_2 + 5}$ [b]
Cristobalite formula calculated	"
Amorphous, including natural diatomaceous earth	20
Silicates (less than 1% crystalline silica)	
Asbestos	5
Mica	20
Soapstone	20
Talc	20
Portland Cement	50
Miscellaneous (less than 1% crystalline silica)[d]	50
Graphite (natural)	
"Inert" or Nuisance Particulates see Appendix D	50 (or 15 mg/m^3 whichever is the smaller)

Conversion factors
mppcf x 35.3 = million particles per cubic meter
= particles per c.c.

Note: Footnotes to Respirable Dusts Evaluated by Count.

[a]Millions of particles per cubic foot of air, based on impinger samples counted by light-field technics.
[b]The percentage of crystalline silica in the formula is the amount determined from air-borne samples, except in those instances in which other methods have been shown to be applicable.

Tentative Values

These substances, with their corresponding tentative limits, comprise those for which a limit has been assigned for the first time or for which a change in the 'Recommended' listing has been made. In both cases, the assigned limits should be considered trial values that will remain in the tentative listing for a period of at least two years, during which time difinitive evidence and experience is sought. If acceptable at the end of two years, these substances and values will be moved to the RECOMMENDED list. Documentation for tentative values are available for each of these substances.

Substance	ppm[a]	mg/m^3 [b]
Acrylamide-skin	--	0.3
2-Aminopyridine	0.5	2
sec-Amyl acetate	125	650
Azinphos-methyl-skin	--	0.2
Bromoform-skin	0.5	5
n-Butyl acetate	150.	710.
sec-Butyl acetate	200	950
tert-Butyl acetate	200.	950.
[e]sec-Butyl alcohol	150.	450.
Cadmium (metal dust and soluble salts)	--	0.2
Carbon black	--	3.5
Carbon monoxide	50.	55.
[e]o-Chloroacetophenone (phenacychloride)	0.05	0.3
o-Chlorobenzylidene malononitrile (OCBM)	.05	0.4
[c]Chlorine	1.	3.
[e]Chromium, sol. chromic, chromous salts, as Cr	--	0.5
metallic and insoluble salts	--	1.
Coal tar pitch volatiles (benzene soluble fraction) (anthracene, BaP, phenanthrene, acridine, chrysene, pyrene)	--	0.2
[e]Cobalt, metal fume and dust	--	0.1
Crotonaldehyde	2.	6.
Cumene-skin	50.	245.
Cyclohexane	300.	1,050.
Cyclohexene	300.	1,015.
Diazomethane	0.2	0.4
[c]1,2-Dibromo-ethane-skin	25.	190.
[d]Dibutyl phosphate	1.	5.
[d]Dibutylphthalate	--	5.
Diethylamino ethanol-skin	10.	50.
[e]Diisopropylamine-skin	5.	20.
[e]Dimethylphthalate	--	5.
[e]Diphenyl	0.2	1.
Ethylamine	10.	18.
Ethyl sec-amyl ketone (5-methyl-3-heptanone)	25.	130.
Ethyl benzene	100.	435.
Ethyl butyl ketone (3-Heptanone)	50.	230.
[c, d]Ethylene glycol dinitrate and/or nitroglycerin-skin	0.02[f]	0.1[f]
Ethylene imine-skin	0.5	1.
[c]Ethyl mercaptan	10.	25.
N-Ethylmorpholine-skin	20.	94.
Fibrous glass	--	5.
Formic acid	5.	9.
[e]Gasoline	A[6]	
sec-Hexyl acetate	50.	300.
[e]Hexachloronaphthalene-skin	--	0.2
Iron oxide fume	--	10.
Isoamyl acetate	100.	525.
Isobutyl acetate	150.	700.
[e]Isobutyl alcohol	100.	300.
Isopropyl acetate	250.	950.
[d]Maleic anhydride	0.25	1.
Methylamine	10.	12.
Methyl (n-amyl) ketone (2-Heptanone)	100.	465.
Methyl iodide-skin	5.	28.
Methyl isocyanate-skin	0.02	0.05
[c]Monomethyl hydrazine-skin	0.2	0.35
[d]Naphtha (coal tar)	100.	400.
[e]Nitric oxide	25.	30.
[e]Octachloronaphthalene-skin	--	0.1
Oxalic acid	--	1.
[e]Parquat-skin	--	0.5
Phenyl ether (vapor)	1.	7.
Phenyl ether-Biphenyl mixture (vapor)	1.	7.
[d]Phenyl glycidyl ether (PGE)	10.	62.
Pival (2-Pivalyl-1,3-indandione)	--	0.1
[e]Propyl alcohol	200.	450
Propylene imine-skin	2.	5.
Rhodium, metal fume and dusts	--	0.1
Soluble salts	--	0.001
[e]Ronnel	--	15.
Selenium hexafluoride	0.05	0.4
Tellurium hexafluoride	0.02	0.2
[c, e]Terphenyls	1.	9.4
[e]Tetrachloronaphthalene-skin	--	2.
Tetramethyl lead (TML) (as lead)-skin	--	0.075
Tetramethyl succinonitrile-skin	0.5	3.
Tremolite	5 mppcf	--
[e]Tributyl phosphate	--	5.
1,1,2-Trichloroethane-skin	10.	45.
Xylene	100.	435.
[e]Zinc chloride	--	1.

Note: Footnotes to Tentative Values.

[a]Parts of vapor or gas per million parts of air plus vapor by volume at 25°C and 760 mm Hg pressure.
[b]Approximate milligrams of particulate per cubic meter of air.
[c]Indicates a value that should not be exceeded.
[d]1966 revision.
[e]1966 additions.
[f]For intermittent exposures only.

"A" Values

A[1] Benzidine. Because of high incidence of bladder tumors in man, any exposure, including skin, is extremely hazardous.

A[2] β-Naphthylamine. Because of the extremely high incidence of bladder tumors in workers handling this compound and the inability to control exposures, β-naphthylamine has been prohibited from manufacture, use and other activities that involve human contact by the State of Pennsylvania.

A[3] N-Nitrosodimethylamine. Because of extremely high toxicity and presumed carcinogenic potential of this compound, contact by any route should not be permitted.

A[4] Polytetrafluoroethylene* decomposition products. Thermal decomposition of the fluorocarbon chain in air leads to the formation of oxidized products containing carbon, fluorine, and oxygen. Because these products decompose by hydrolysis in alkaline solution, they can be quantitatively determined in air as fluoride to provide an index of exposure. No TLV is recommended pending determination of the toxicity of the products, but air concentrations should be minimal.

A[5] βPropiolactone. Because of high acute toxicity and demonstrated skin tumor production in animals, contact by any route should be avoided.

A[6] Gasoline. The composition of gasoline varies greatly and thus a single TLV for all types of gasoline is no longer applicable. In general, the aromatic hydrocarbon content will determine what TLV applies. Consequently the content of benzene, other aromatics and additives should be determined to arrive at the appropriate TLV (Elkins, et al., A.I.H.A.J. 24, 99, 1963).

*Trade Names: Algoflon, Fluon, Halon, Teflon, Tetran

Table D3. ENTHALPIES OF VARIOUS GASES EXPRESSED IN Btu/lb OF GAS

Temp, °F	CO_2	N_2	H_2O[a]	O_2	Air
100	5.8	6.4	17.8	8.8	9.6
150	17.6	20.6	40.3	19.8	21.6
200	29.3	34.8	62.7	30.9	33.6
250	40.3	47.7	85.5	42.1	45.7
300	51.3	59.8	108.2	53.4	57.8
350	63.1	73.3	131.3	64.8	70.0
400	74.9	84.9	154.3	76.2	82.1
450	87.0	97.5	177.7	87.8	94.4
500	99.1	110.1	201.0	99.5	106.7
550	111.8	122.9	224.8	111.3	119.2
600	124.5	135.6	248.7	123.2	131.6
700	150.2	161.4	297.1	147.2	156.7
800	176.8	187.4	346.4	171.7	182.2
900	204.1	213.8	396.7	196.5	211.4
1,000	231.[illegible]	240.5	447.7	221.6	234.1
1,100	260.2	267.5	499.7	247.0	260.5
1,200	289.0	294.9	552.9	272.7	287.2
1,300	318.0	326.1	606.8	298.5	314.2
1,400	347.6	350.5	661.3	324.6	341.5
1,500	377.6	378.7	717.6	350.8	369.0
1,600	407.8	407.3	774.2	377.3	396.8
1,700	438.2	435.9	831.4	403.7	424.6
1,800	469.1	464.8	889.8	430.4	452.9
1,900	500.1	493.7	948.7	457.3	481.2
2,000	531.4	523.0	1,003.1	484.5	509.5
2,100	562.8	552.7	1,069.2	511.4	538.1
2,200	594.3	582.0	1,130.3	538.6	567.1
2,300	626.2	612.3	1,192.6	566.1	596.1
2,400	658.2	642.3	1,256.8	593.5	625.0
2,500	690.2	672.3	1,318.1	621.0	654.3
3,000	852.3	823.8	1,640.2	760.1	802.3
3,500	1,017.4	978.0	1,975.4	901.7	950.3

[a] The enthalpies tabulated for H_2O represent a gaseous system, and the enthalpies do not include the latent heat of vaporization. It is recommended that the latent heat of vaporization at 60°F (1,059.9 Btu/lb) be used where necessary.

Table D4. ENTHALPIES OF GASES EXPRESSED IN Btu/scf OF GAS, REFERENCE 60°F

°F	N_2	O_2	Air	H_2	CO	CO_2	H_2O[a]
60	-	-	-	-	-	-	-
77	0.31	0.31	0.32	0.31	0.32	0.39	0.36
100	0.74	0.74	0.74	0.73	0.74	0.94	0.85
200	2.58	2.61	2.58	2.55	2.58	3.39	2.98
300	4.42	4.50	4.42	4.40	4.43	5.98	5.14
400	6.27	6.43	6.29	6.24	6.29	8.69	7.33
500	8.14	8.40	8.17	8.09	8.18	11.52	9.52
600	10.02	10.40	10.07	9.89	10.08	14.44	11.81
700	11.93	12.43	12.00	11.77	12.01	17.45	14.11
800	13.85	14.49	13.95	13.61	13.96	20.54	16.45
900	15.80	16.59	15.92	15.47	15.94	23.70	18.84
1,000	17.77	18.71	17.92	17.36	17.94	26.92	21.27
1,100	19.78	20.85	19.94	19.20	19.97	30.21	23.74
1,200	21.79	23.02	21.98	21.08	22.02	33.55	26.26
1,300	23.84	25.20	24.05	22.95	24.10	36.93	28.82
1,400	25.90	27.40	26.13	24.87	26.19	40.36	31.42
1,500	27.98	29.62	28.24	26.80	28.31	43.85	34.08
1,600	30.10	31.85	30.38	28.70	30 44	47.35	36.77
1,700	32.21	34.10	32.50	30.62	32.58	50.89	39.49
1,800	34.34	36.34	34.66	32.52	34.74	54.48	42.26
1,900	36.48	38.61	36.82	34.45	36.93	58.07	45.06
2,000	38.65	40.90	38.99	36.43	39.12	61.71	47.91
2,100	40.84	43.17	41.18	38.49	41.31	65.35	50.78
2,200	43.00	45.47	43.39	40.57	43.53	69.02	53.68
2,300	45.24	47.79	45.61	42.66	45.74	72.71	56.64
2,400	47.46	50.11	47.63	44.71	47.99	76.43	59.59
2,500	49.67	52.43	50.07	46.82	50.23	80.15	62.60
3,000	60.91	64.18	61.39	57.22	61.55	98.96	77.98
3,500	72.31	76.13	72.87	68.14	73.00	118.15	93.92
4,000	83.79	88.29	84.42	79.38	84.56	137.62	110.28
4,500	95.37	100.64	96.11	90.68	96.21	157.20	126.96
5,000	107.04	113.20	107.91	102.42	107.93	176.93	143.92
5,500	118.78	125.89	119.78	114.21	119.70	196.77	161.07
6,000	132.54	139.74	131.73	126.16	131.52	216.77	178.41
6,500	142.37	151.72	143.76	138.35	143.37	236.88	195.82

[a]Enthalpies are for a gaseous system, and do not include latent heat of vaporization. L_v = 1,059.9 Btu/lb or 50.34 Btu/scf of H_2O vapor at 60°F and 14.696 psia.

Table D5. TYPICAL PHYSICAL PROPERTIES OF FUEL OILS

Pacific standard No.		PS No. 100		PS No. 200	PS No. 300	PS No. 400
Grade		1	2	3	5	6
Common name		Kerosine	Distillate	Straight-run fuel oil	Low-crack fuel oil	Heavy-crack fuel oil
Typical analysis	Carbon (C)	84.7%		85.8%	87.5%	88.3%
	Hydrogen (H)	15.3%		12.1%	10.2%	9.5%
	Sulfur (S)[d]	0.02%		1.2%	1.1%	1.2%
	Water (H_2O)	-		-	0.05%	0.05%
	Other	-		0.9%	1.1%	1.0%
	(°Be')	41.8°		26.2°	16.5°	8.9°
	lb/gal	6.83		7.50	8	8.33
	Sp gr 60°/60°	0.82		0.90	0.96	1
	Approximate Btu/gal	136,000		142,000	146,000	152,000
	Approximate Btu/lb	19,910		18,950	18,250	18,000
		1	2			
Specifications	Max viscosity	-	-	45 sec (100°F)[b]	40 sec (122°F)[c]	300 sec (122°F)[c]
	Flash) Min	110°F	125°F	150°F	150°F	150°F
	point) Max	165°F[a]	190°F[a]	200°F[a]	-	-
	Max water and sediment	0.05%	0.05%	0.1%	1.0%	2.0%
	Max 10% point	420°F	440°F	460°F	-	-
	Max 90% point	-	620°F	675°F	-	-
	Max endpoint	600°F	-	-	-	-

[a]Or legal maximum.
[b]Saybolt Universal.
[c]Saybolt Furol.
[d]Sulfur contents are only typical and will vary in different locales.

Table D6. COMBUSTION DATA BASED ON 1 POUND OF FUEL OIL[a, b, c]

Constituent		PS No. 100		PS No. 200		PS No. 300		PS No. 400	
		ft^3	lb	ft^3	lb	ft^3	lb	ft^3	lb
Theoretical air (40% sat'd at 60°F)		197.3	15.04	185.1	14.11	179.1	13.66	177.2	13.51
Flue gas constituents with theoretical air	CO_2	26.73	3.104	27.08	3.144	27.61	3.207	27.86	3.236
	SO_2	0.002	0.0004	0.142	0.0240	0.130	0.0220	0.142	0.0240
	N_2	154.8	11.44	145.2	10.74	140.5	10.39	139.0	10.28
	H_2O formed	28.76	1.368	22.75	1.082	19.18	0.9118	17.86	0.8491
	H_2O (fuel)	-	-	-	-	0.011	0.0005	0.011	0.0005
	H_2O (air)	1.367	0.0662	1.283	0.0621	1.242	0.0601	1.228	0.0595
Total		211.659	15.9786	196.455	15.0521	188.673	14.5914	186.101	14.4491
Amount of flue gas with % excess air as indicated	0	211.7	15.98	196.5	15.05	188.7	14.59	186.0	14.45
	7.5	226.5	17.11	210.4	16.11	202.1	15.62	199.4	15.46
	10	231.4	17.48	215.0	16.46	206.6	15.96	203.8	15.80
	12.5	236.4	17.86	219.6	16.81	211.1	16.30	208.3	16.14
	15	241.3	18.24	224.3	17.17	215.6	16.64	212.7	16.48
	17.5	246.2	18.61	228.9	17.52	220.0	16.98	217.1	16.81
	20	251.2	18.99	233.5	17.87	224.5	17.32	221.5	17.15
	30	270.9	20.49	252.0	19.28	242.4	18.69	239.3	18.50
	40	290.6	22.00	270.5	20.69	260.3	20.05	257.0	19.85
	50	310.4	23.50	289.1	22.11	278.3	21.42	274.7	21.21
	75	359.7	27.26	335.3	25.63	323.0	24.84	319.0	24.58
	100	409.0	31.02	381.6	29.16	367.8	28.25	363.3	27.96
SO_2 % by vol and wt with theoretical air		0.0011	0.0025	0.072	0.16	0.069	0.15	0.076	0.17

[a]Combustion products calculated for combustion with air 40% saturated at 60°F. All volumes measured as gases at 60°F. Moisture in fuel included where indicated.
[b]Maximum accuracy of calculations: 1:1000.
[c]Based on physical properties in Table D5.

Table D7. COMBUSTION CHARACTERISTICS OF NATURAL GAS

Average analysis, volume %[a]

CO_2	0
N_2	5.15
O_2	0
CH_4	81.11
C_2H_6	9.665
C_3H_8	3.505
i-C_4H_{10}	0.19
n-C_4H_{10}	0.24
C_{5+}	0.09
C_{6+}	0.05
	100.00

Average gross heat, 1,100 Btu/ft^3

Air required for combustion

Theoretical - 10.360 ft^3/ft^3 gas

20% excess air - 12.432 ft^3/ft^3 gas

Products of combustion/ft^3 of gas

	Theoretical air		20% excess air	
	Vol	Wt	Vol	Wt
CO_2	1.134 ft^3	0.132 lb	1.134 ft^3	0.132 lb
H_2O	2.083	0.099	2.083	0.099
N_2	8.236	0.609	9.873	0.731
O_2	-		0.435	0.037
Total	11.453 ft^3	0.840 lb	13.525 ft^3	0.999 lb

Available heat, Btu/ft^3 gas,[a] based on latent heat of vaporization of water at 60°F

Temp, °F	Available heat, Btu, with theoretical air	Available heat, Btu, 20% excess air
100	988.6	992.2
150	976.1	973.0
200	963.7	958.5
250	952.1	949.9
300	941.0	932.0
350	928.8	917.8
400	917.8	905.1
450	906.2	891.5
500	894.6	878.0
550	882.7	864.1
600	870.9	850.4
700	846.2	821.8
800	820.7	792.3
900	797.7	765.3
1,000	772.6	736.2
1,100	747.2	706.6
1,200	721.3	676.5
1,300	693.0	643.6
1,400	668.6	615.4
1,500	642.7	584.5
1,600	614.6	552.9
1,700	589.8	523.7
1,800	562.3	491.7
1,900	534.8	459.9
2,000	507.5	428.2
2,100	478.7	394.9
2,200	450.7	362.5
2,300	421.9	329.1
2,400	393.0	295.6
2,500	364.6	262.6
3,000	219.1	94.2
3,500	70.4	--

[a]Average of two samples analyzed by Southern Calif. Gas Co., 1956.

Table D8. CONVERSION TABLE OF VELOCITY (V) TO VELOCITY PRESSURE (VP)

Velocity, fpm	VP at 70°F in. WC	VP at 60°F in. WC	Velocity, fpm	VP at 70°F in. WC	VP at 60°F in. WC	Velocity, fpm	VP at 70°F in. WC	VP at 60°F in. WC
800	0.040	0.041	2,550	0.406	0.414	4,300	1.152	1.174
850	0.045	0.046	2,600	0.421	0.429	4,350	1.179	1.202
900	0.051	0.052	2,650	0.438	0.446	4,400	1.208	1.231
950	0.056	0.057	2,700	0.454	0.463	4,450	1.235	1.259
1,000	0.062	0.063	2,750	0.472	0.481	4,500	1.262	1.286
1,050	0.069	0.070	2,800	0.489	0.498	4,550	1.291	1.316
1,100	0.075	0.077	2,850	0.507	0.517	4,600	1.319	1.344
1,150	0.082	0.084	2,900	0.524	0.534	4,650	1.348	1.374
1,200	0.090	0.092	2,950	0.543	0.553	4,700	1.377	1.403
1,250	0.097	0.099	3,000	0.561	0.572	4,750	1.407	1.434
1,300	0.105	0.107	3,050	0.581	0.592	4,800	1.435	1.463
1,350	0.114	0.116	3,100	0.599	0.611	4,850	1.466	1.494
1,400	0.122	0.124	3,150	0.618	0.630	4,900	1.496	1.525
1,450	0.131	0.134	3,200	0.638	0.650	4,950	1.527	1.556
1,500	0.140	0.143	3,250	0.658	0.671	5,000	1.558	1.588
1,550	0.150	0.153	3,300	0.678	0.691	5,050	1.590	1.621
1,600	0.160	0.163	3,350	0.699	0.712	5,100	1.621	1.652
1,650	0.170	0.173	3,400	0.720	0.734	5,150	1.654	1.686
1,700	0.180	0.184	3,450	0.742	0.756	5,200	1.685	1.717
1,750	0.191	0.195	3,500	0.764	0.779	5,250	1.718	1.751
1,800	0.202	0.206	3,550	0.785	0.800	5,300	1.751	1.785
1,850	0.213	0.217	3,600	0.808	0.824	5,350	1.784	1.818
1,900	0.225	0.229	3,650	0.830	0.846	5,400	1.817	1.852
1,950	0.237	0.242	3,700	0.853	0.869	5,450	1.851	1.887
2,000	0.249	0.254	3,750	0.876	0.893	5,500	1.886	1.922
2,050	0.262	0.267	3,800	0.900	0.917	5,550	1.919	1.956
2,100	0.275	0.280	3,850	0.924	0.942	5,600	1.955	1.993
2,150	0.288	0.294	3,900	0.948	0.966	5,650	1.991	2.029
2,200	0.301	0.307	3,950	0.973	0.992	5,700	2.026	2.065
2,250	0.316	0.322	4,000	0.998	1.017	5,750	2.061	2.101
2,300	0.329	0.335	4,050	1.022	1.042	5,800	2.098	2.138
2,350	0.344	0.351	4,100	1.049	1.069	5,850	2.134	2.175
2,400	0.359	0.366	4,150	1.073	1.094	5,900	2.170	2.212
2,450	0.375	0.382	4,200	1.100	1.122	5,950	2.207	2.249
2,500	0.389	0.396	4,250	1.126	1.148	6,000	2.244	2.287

Table D9. DENSITIES OF TYPICAL SOLID MATERIALS AS THEY OCCUR IN MATERIAL-HANDLING AND PROCESSING OPERATIONS

Material	Densities, lb/ft^3
Ashes, dry, loose	38
Ashes, wet, loose	47
Baking powder	56
Bone, ground, dry	75
Borax	105 to 110
Calcium carbide, crushed	
3-1/2 in. x 2 in., loose	77
2 in. x 1/2 in., loose	75
1/2 in. x 1/8 in., loose	80
1/8 in. x 0 in., loose	82
Carbon, activated, very fine, dry	8 to 20
Cement, Portland, loose	94
Cement, Portland, clinker	95
Charcoal, broken, all sizes	15 to 30
Charcoal, broken, 1-1/2 in. x 0 in.	14
Charcoal, ground	10
Chips, wood	18
Cinders, blast furnace	57
Cinders, coal, ashes, and clinker	40
Clay, dry in lumps, loose	63
Coal, anthracite, broken, loose	55 to 60
Coal, bituminous, broken, loose	50 to 54
Coal, bituminous, 5 in. x 0 in., dry	54
Coal, bituminous, 1/2 in. x 0 in., dry	45
Coal, bituminous, 1/8 in. x 0 in., dry	43
Coke, lump, average	28 to 32
Coke, breeze	30 to 34
Coke, petroleum, lump	40 to 50
Cork, solid	15
Cork, in bales	8 to 9
Cork, ground, 10 in. mesh x 0 in.	4 to 5
Cullet, glass, average	85 to 100
Cullet, glass, 3/4 in. x 0 in.	80 to 90
Dolomite, crushed, 2 in. x 1/2 in.	94
Dolomite, crushed, 1/2 in. x 0 in.	98
Earth, common loam, dry, loose	76
Earth, common loam, moist, loose	73
Feldspar, broken, in loose piles	90 to 100
Fluorspar, broken, in loose piles	110 to 125
Fluorspar, ground, 100 mesh x 0 in.	90 to 100
Flint, pebbles	105
Fullers Earth, dry	30 to 35
Glass batch	90 to 110
Gniess, broken, in loose piles	96
Granite, broken, in loose piles	96
Granite, crushed, 1-1/4 in. x 10 mesh	98
Gravel, mixed sizes, loose	96 to 100
Gravel, 2 in. x 1/4 in., loose	105 to 110
Gravel, 3/4 in. x 1/8 in., loose	98 to 100
Greenstone, broken, in loose piles	107

Material	Densities, lb/ft^3
Gypsum, broken, in loose piles	90 to 94
Gypsum, crushed, 1 in. x 0 in., loose	90
Gypsum, ground, loose	50 to 56
Iron (cast) borings, fine	120 to 155
Iron ore, loose	125 to 150
Lime, hydrated, -200 mesh	20 to 25
Lime, quick, lump, 1-1/2 in. x 0 in.	70 to 80
Lime, quick, lump, 1/2 in. x 0 in.	70
Lime, quick, ground	60 to 65
Lime, quick, from oyster shells, loose	45 to 50
Limestone, broken, in loose piles	95
Limestone, sized 3 in. x 2 in., loose	95
Limestone, sized, 2 in. x 1/2 in., loose	92
Limestone, sized, 1/2 in. x 0 in., loose	96
Limestone, ground, -50 mesh, loose	84
Limestone, ground, -200 mesh, loose	65
Marble, crushed	95
Oyster shells, piled	60
Phosphate rock, broken, in loose piles	75 to 85
Phosphate rock, pebble	90 to 100
Quartz, broken, in loose piles	94
Rubber, shredded scrap	46
Salt, coarse	45 to 52
Salt, fine	42 to 50
Salt, table	42 to 45
Salt, rock, broken, in loose piles	50
Salt, cake, coarse	55 to 60
Salt, cake, fine	45 to 50
Sand, dry, loose	90 to 95
Sand, wet, loose	105 to 110
Sand and gravel, dry	90 to 105
Sand and gravel, wet	105 to 125
Sand, molding, prepared and loose	77 to 80
Sand, molding, rammed	90 to 100
Sand, molding, shaken out or new	100
Sandstone, broken, in loose piles	82 to 86
Sawdust, dry	7 to 12
Scale, rolling mill	105
Shale, crushed, in loose piles	92
Slag, bank, crushed	80
Slag, furnace, granulated	60
Soda ash, dense	60 to 62
Soda ash, light	28 to 32
Soda, bicarbonate, loose	50 to 58
Starch, granular	22 to 25
Stone, crushed, 1 in. x 0 in.	85 to 105
Sugar, granulated, loose	42 to 50
Sugar, brown	45 to 55
Sulphur, ground, -100 mesh	75 to 85
Sulphur, ground, -200 mesh	50 to 55
Trap rock, broken, in loose piles	107
Trap rock, crushed	95 to 105

Table D10. WEIGHTS AND DILUTIONS OF LACQUERS AND ENAMELS USED IN LOS ANGELES COUNTY

Company	Wt, lb/gal					Nonvolatiles % by wt			Thinning[a] % by vol		
	Thinner		Undiluted paints								
	Lacquer	Enamel	Lac (dk)	Lac (lt)	Enamel	Lac (cl)	Lac (col)	Enamel	Lacquer	Enamel	
Pittsburgh Plate Glass	6.5 to 7.5	6.5 to 7.5	8	9	9 to 10	25	40 to 45	40 to 50	80 to 100	20 to 25	
Ferro Enamel Paint	7.2 to 7.3	7.2 to 7.3	9 to 10	9 to 10	9 to 10	25 to 30	35 to 40	50	50 to 200	10 to 20	
National Lead Company	8.5	6.5 to 7.0	8 to 8.5	7.5 to 8	8 to 9.5	25	40 to 50	50	100 to 150	20 to 25	$ZnCrO_4$ - 60% solids thin 1:2
Andrew Brown Company	6.8 to 6.9	7.0	-	-	8.5 to 10	20 to 25	35 to 40	45 to 55	100	20 to 35	$ZnCrO_4$ - 60% solids thin 1:2-1/2
Average	7.4	7.0	8.6	8.8	9.2	25	40	49	110	22	

[a]Based on volume of original paint.

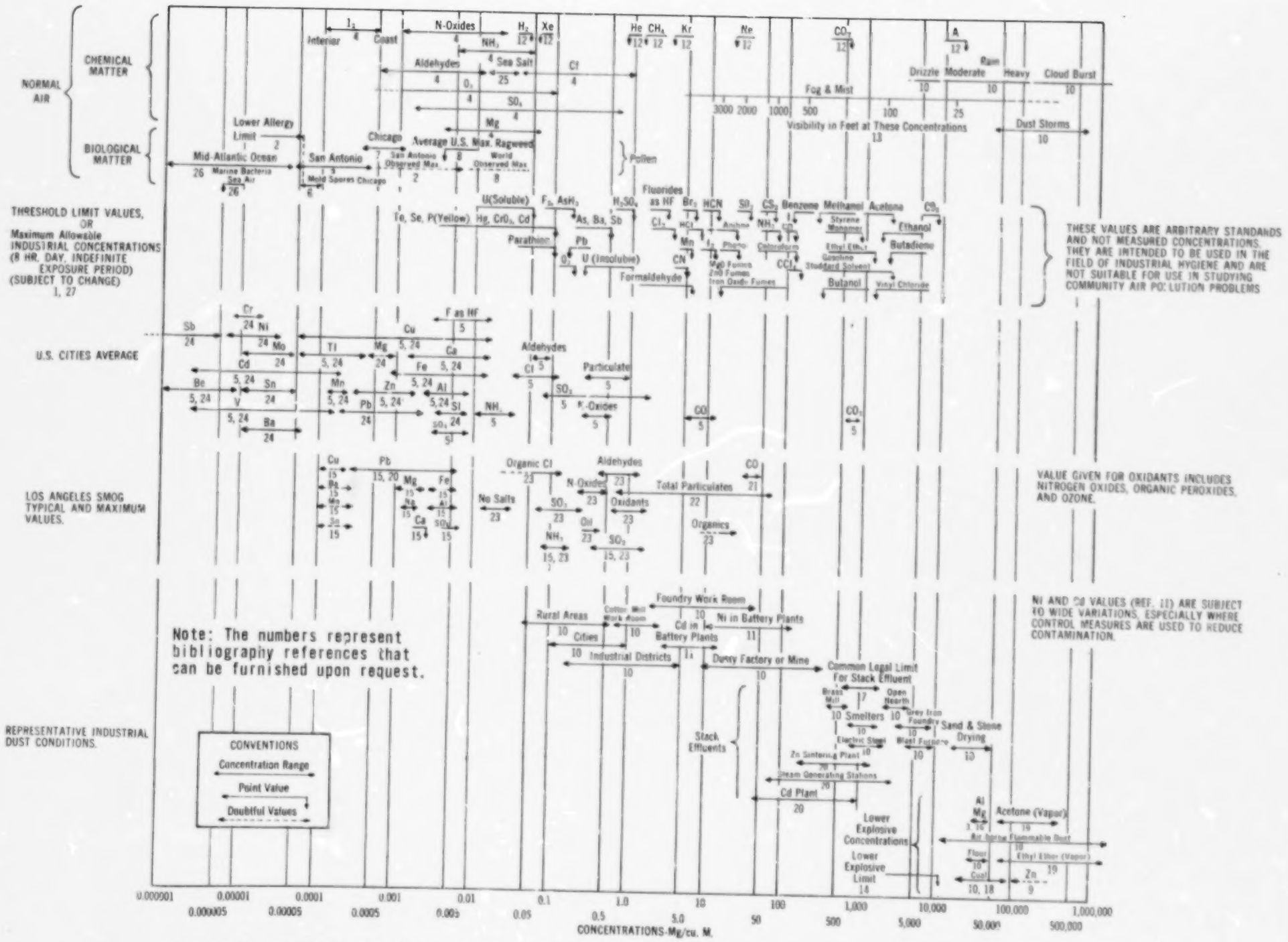
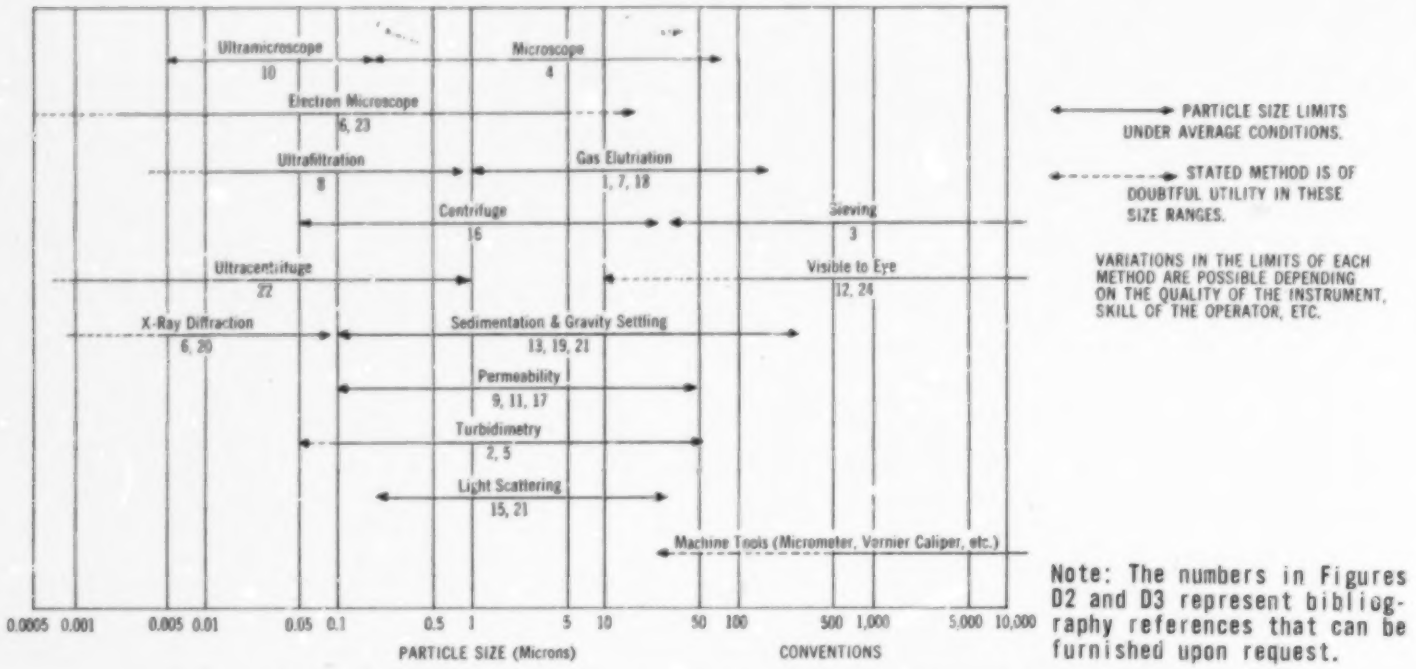


Figure D1. The concentrations of materials in the air (Issued as a public service by Mines Safety Appliances Co., 201 N. Braddock Ave., Pittsburgh, Pa. Prepared by Southwest Research Institute.).



Note: The numbers in Figures D2 and D3 represent bibliography references that can be furnished upon request.

Figure D2. Limits of particle size-measuring equipment (Issued as a public service by Mines Safety Appliances Co., 201 N. Braddock Ave., Pittsburgh, Pa. Prepared by Southwest Research Institute.).

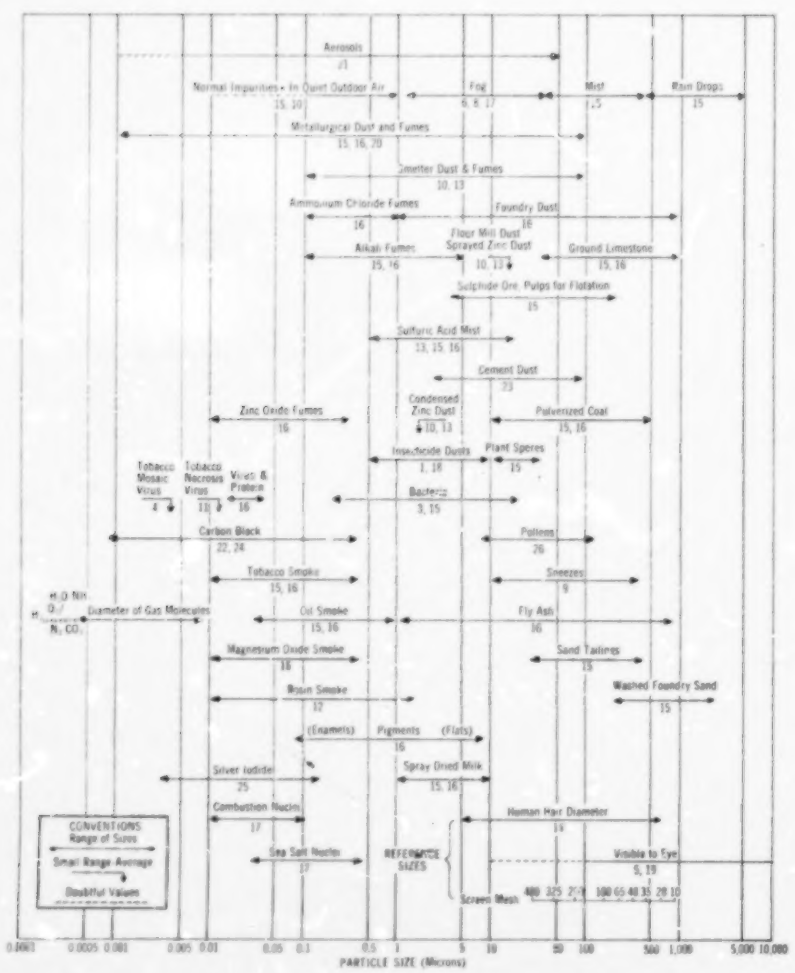


Figure D3. Sizes of airborne contaminants (Issued as a public service by Mines Safety Appliances Co., 201 N. Braddock Ave., Pittsburgh, Pa. Prepared by Southwest Research Institute.).

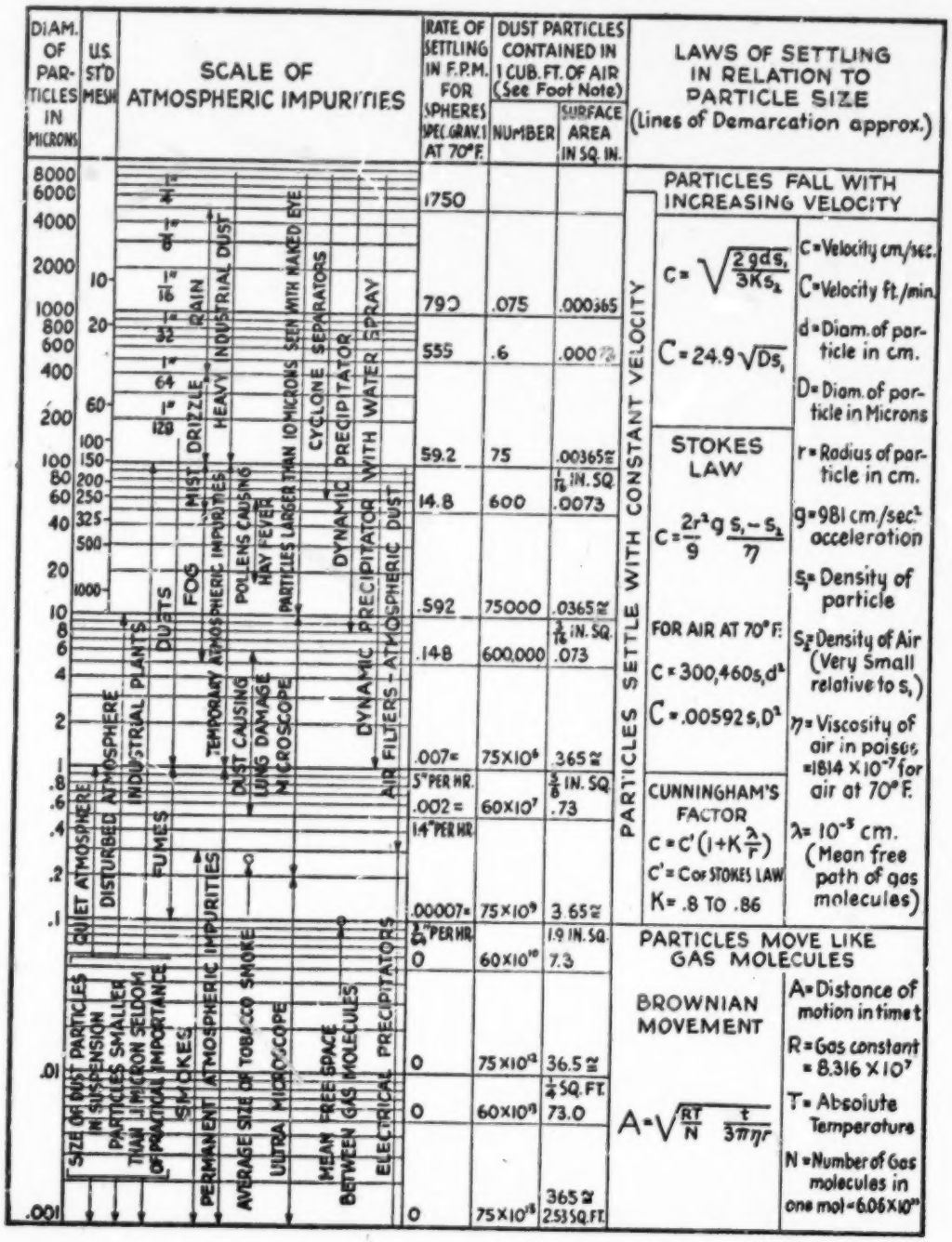


Figure 04. The Frank Chart: Size and characteristics of airborne solids. It is assumed that the particles are of uniform spherical shape having specific gravity 1 and that the dust concentration is 0.6 grain per 1,000 ft^3 of air, the average of metropolitan districts. (Compiled by W.G. Frank, Copyrighted by American Air Filter Co., Inc., Dust Control Products, Louisville, Ky.).

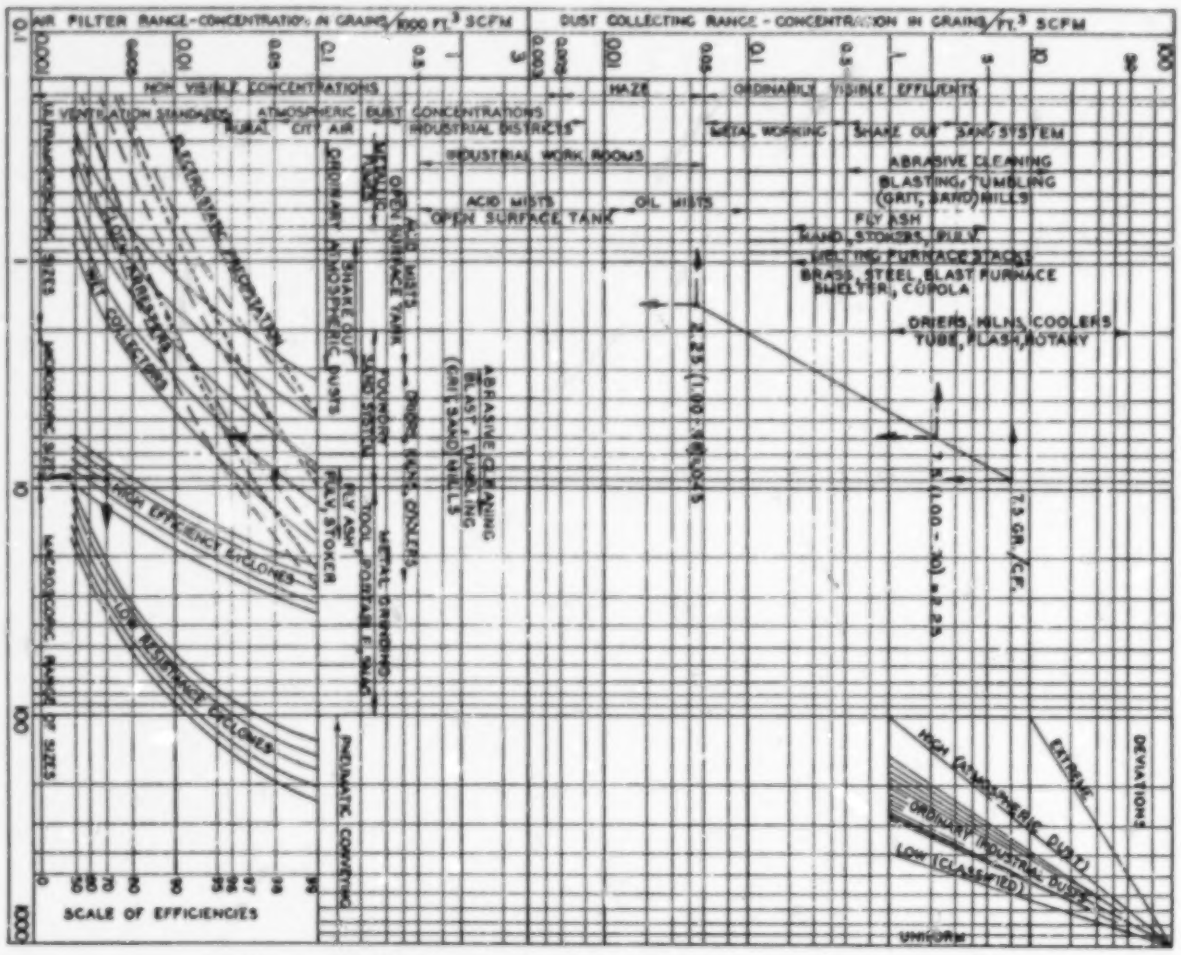


Figure D5. Range of particle sizes, concentrations, and collector performance (Compiled by S. Sylvan, April 1952- Copyright, 1952, American Air Filter Co., Inc., Louisville, Ky.).

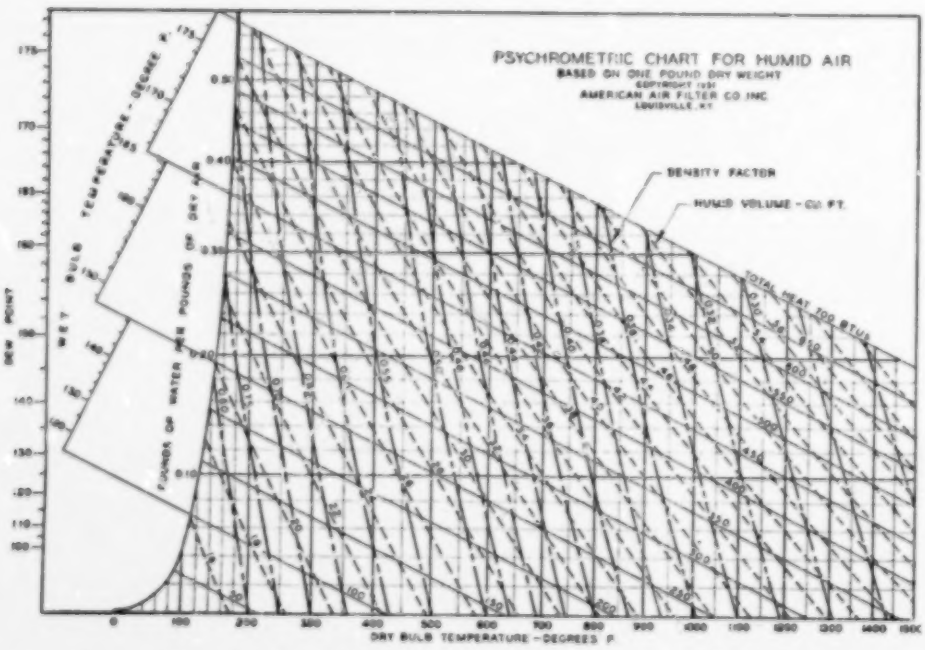

PSYCHROMETRIC CHART FOR HUMID AIR
BASED ON ONE POUND DRY WEIGHT
AMERICAN AIR FILTER CO INC
LOUISVILLE, KY
DENSITY FACTOR
HUMID VOLUME - CU FT.
TOTAL HEAT 100 BTUS
DEW POINT
WET BULB TEMPERATURE - DEGREES F.
POUNDS OF WATER PER POUNDS OF DRY AIR
DRY BULB TEMPERATURE - DEGREES F

Figure D6. Psychrometric chart for humid air based on 1 lb dry weight. (Copyright, 1951, American Air Filter Co., Inc., Louisville, Ky.).

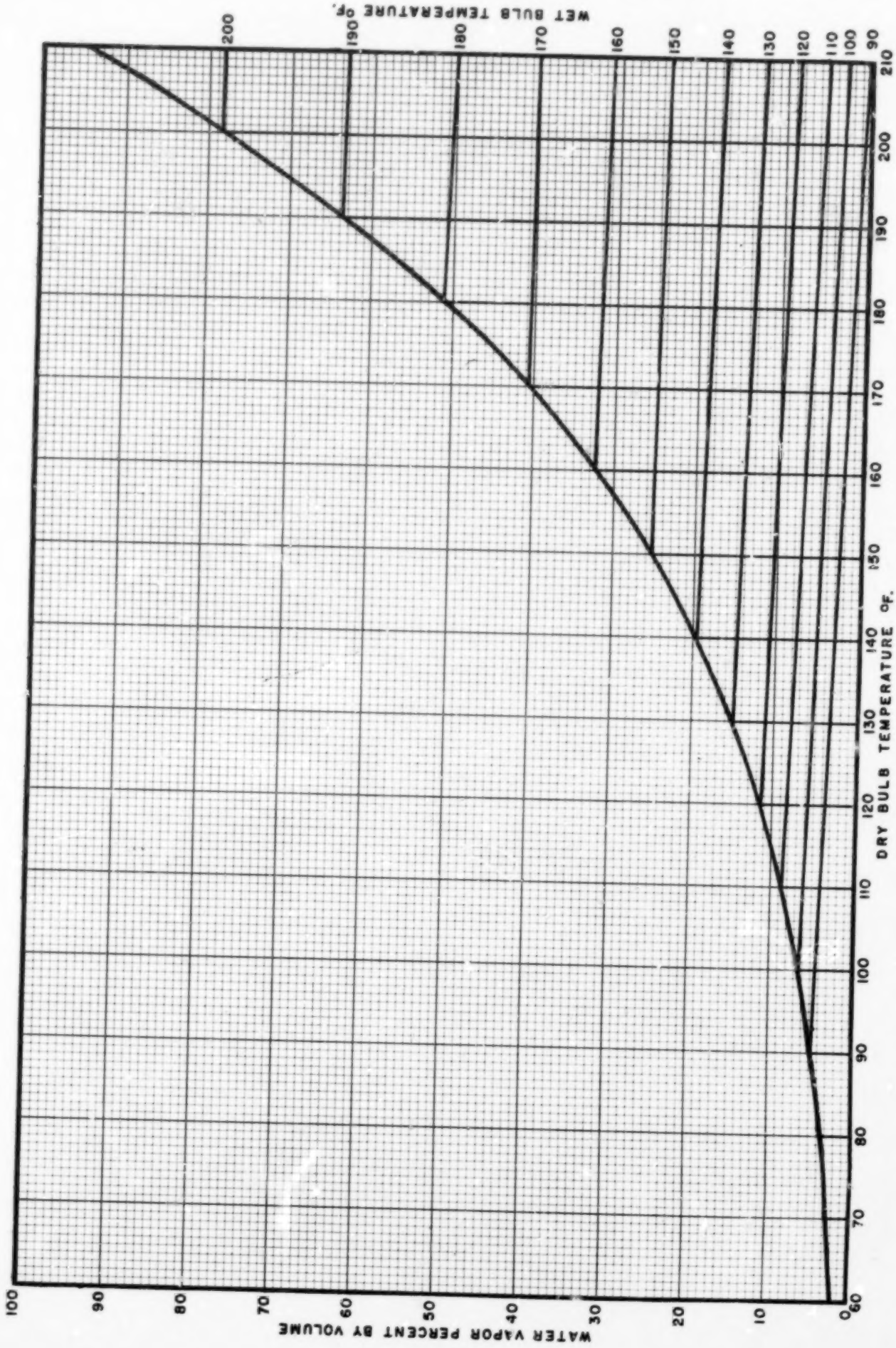


Figure D7. High-temperature psychrometric chart for air-water vapor mixtures at 1 atm (29.921 in. Hg).

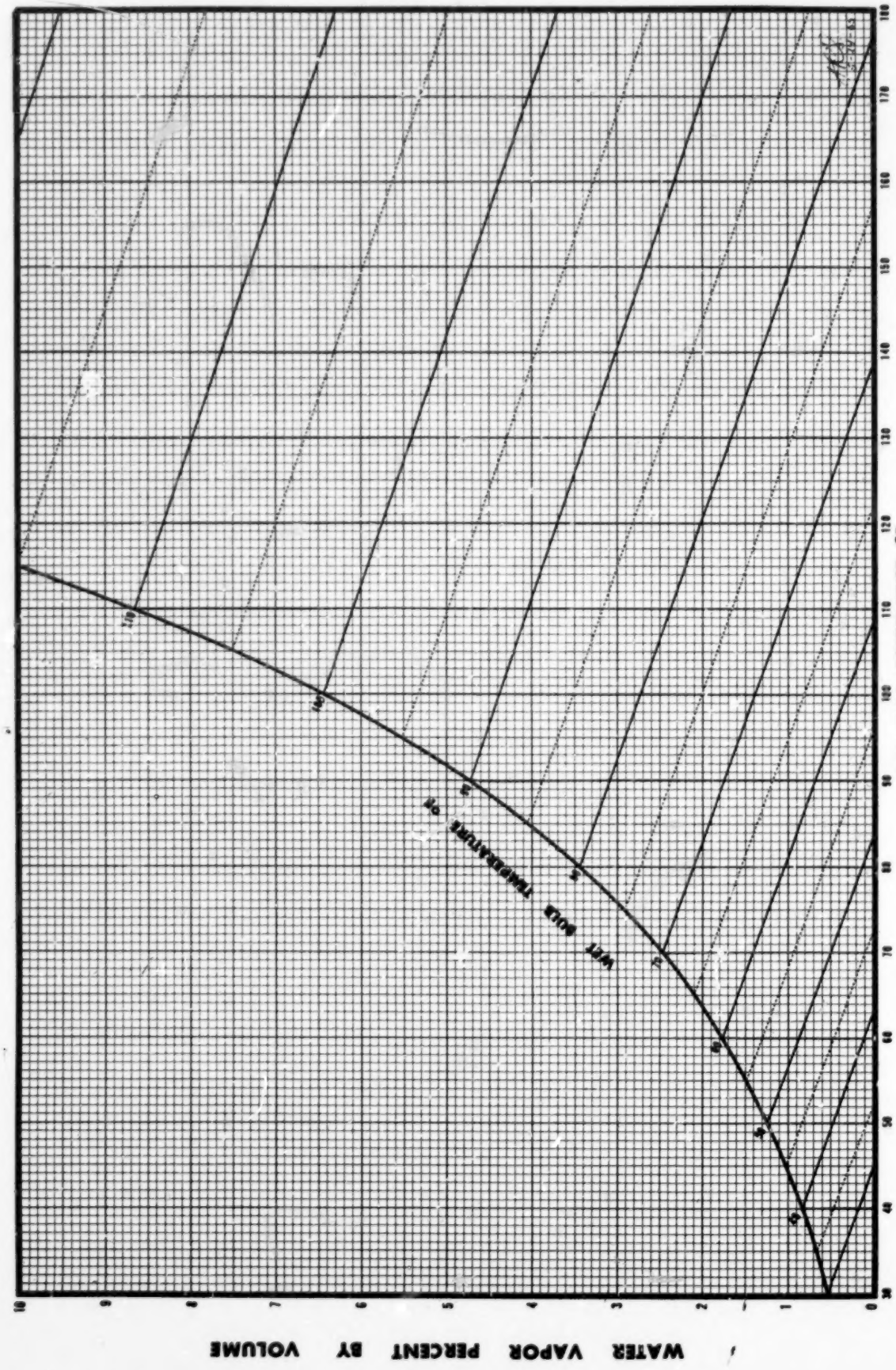


Figure D8. Psychrometric chart expressing volume of water vapor by %.